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MITRE TECHNICAL REPORT

Frequency Assignment Function for UAS C2 Links

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Abstract

This report presents a concept of operations, a high-level description of functional and performance requirements, and supporting analyses for the initial version of a Frequency Assignment Function (FAFu) that will support the command and control (C2) of unmanned aircraft systems (UAS) operating in the National Airspace System. The primary purpose of FAFu is to enable the timely assignment of operating frequencies to terrestrial UAS C2 radio links upon request from UAS operators, while conserving radio-frequency (RF) spectrum and protecting against mutual RF interference among those links and other users of the spectrum.

Acknowledgments

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1 Introduction

Unmanned aircraft systems (UAS) require highly reliable command and control (C2) radio links to enable their pilots to operate them safely within the National Airspace System (NAS). Recognizing this, RTCA recently published a Minimum Operational Performance Standards (MOPS) document, DO-362, for terrestrial UAS C2 links that will operate in the 960–1164 and 5030–5091 megahertz (MHz) frequency bands [1]. In the 960–1164 MHz band, only the 1040–1080 and 1104–1150 MHz frequency ranges are currently being considered for UAS C2 use. Additional operating bands may be identified in future versions of DO-362.

The DO-362 document and RTCA SC-228, the committee that wrote it, generally refer to the radio-frequency (RF) segments of UAS C2 links as "control and non-payload communications (CNPC)" to conform to International Telecommunication Union (ITU) Radiocommunication Sector (ITU-R) terminology. The rest of this report adheres consistently to the "CNPC" nomenclature in referring to the RF links that carry UAS C2 signals.

The ability of the NAS to accommodate a rapidly expanding population of UAS using DO-362-compliant CNPC links will depend heavily on effective use of the radio spectrum available for those links. DO-362 includes provisions for protecting CNPC links against mutual RF interference (RFI), provided that proper procedures are followed when assigning frequencies and RF channels to those links. Effective implementation of such procedures will require development of an automated Frequency Assignment Function (FAFu) that, under the management of a Central Spectrum Authority (CSA), will respond in near-real time to CNPC frequency requests from UAS operators before and during unmanned aircraft (UA) flights.

FAFu will identify candidate frequencies and screen them using established interference-avoidance rules to ensure compatibility with all preexisting CNPC frequency assignments, as well as with non-CNPC frequency assignments in the same bands. It will model equipment and environmental parameters to the extent necessary to prevent RFI. It will temporarily assign one or more frequencies to each requesting UAS for use by its CNPC links in the specified UA flight areas and time windows.

The design of FAFu will utilize appropriate elements of existing air/ground radio frequency-assignment procedures [2] and automated models [3]. It will also incorporate new analytical features necessitated by the challenging requirements of CNPC links operating in the frequency bands specified in DO-362. The greatest challenge will be the unprecedented need to provide frequency assignments, often on very short notice, to hundreds and eventually thousands of UAS operators daily.

It should be noted that neither the Federal Aviation Administration (FAA) nor any other public or private entity has yet made any commitment with respect to the development or operation of FAFu, or to undertake the role of the CSA.

1.1 Organization of Report

This report provides a concept of operations (CONOPS), a high-level description of functional and performance requirements, and a preliminary list of input and output data for FAFu. The remainder of this report is organized as follows:

- Section 2 presents a CONOPS for the initial version of FAFu, including data exchanges with users, frequency-selection procedures, and management interventions.
- Section 3 describes the interference model underlying FAFu and its procedures for ensuring adequate frequency separations between spatially neighboring CNPC links.
- Section 4 explains methods for calculating interference rejection by a CNPC receiver as a function of its frequency separation from a potentially interfering signal.
- Section 5 explains the antenna model to be used by FAFu in determining the degree of interference protection conferred by CNPC ground-antenna directivity.
- Section 6 explains FAFu's model for predicting the RF propagation losses of potentially interfering signals.
- Section 7 describes FAFu's principal input and output data elements.
- Section 8 explains methods to be used in FAFu to enhance the efficiency of its algorithms for screening and selecting frequencies.
- Section 9 describes potential future enhancements to FAFu.
- Section 10 presents a phased implementation plan for FAFu.
- Section 11 presents MITRE's recommendations for development and use of FAFu.
- Appendix A formally defines several important FAFu use cases.
- Appendix B presents a sequence diagram for the most important FAFu use case: the processing of a user's request for a frequency assignment.
- Appendix C is a glossary of acronyms.

2 Concept of Operations

FAFu will enable the timely assignment of operating frequencies to standalone (non-networked) terrestrial CNPC links upon request from UAS operators, in a manner that will conserve radio spectrum while protecting against RFI. FAFu may also be used to allot geographically limited blocks of spectrum to UAS C2 networks whose providers could then use their own procedures to subdivide those blocks in frequency, time, and space among their customers' CNPC links. FAFu will be managed by a Central Spectrum Authority responsible for all terrestrial CNPC assignments within one or more frequency bands across the United States (U.S.). Whether the CSA will be a governmental entity, or a nongovernmental entity to which assignment authority will be delegated, is an issue yet to be resolved.

Figure 2-1 provides an overview of FAFu operation.

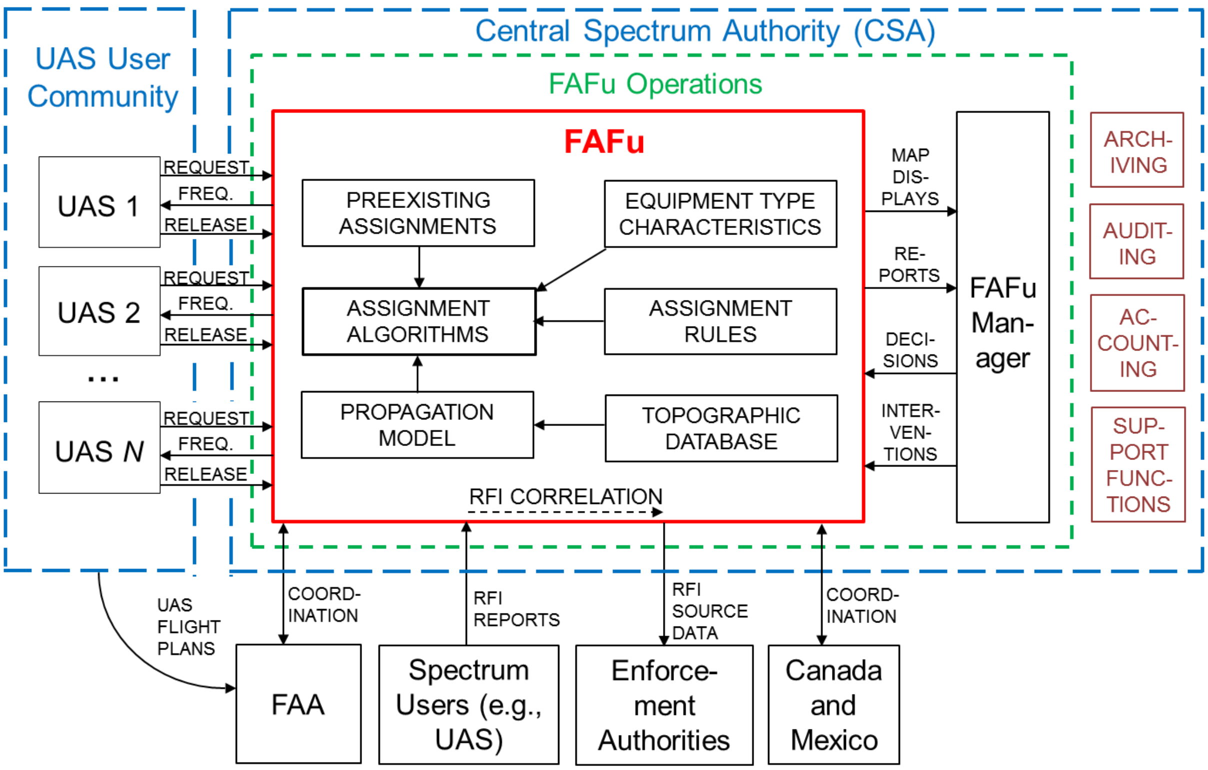


Figure 2-1. Overview of FAFu Operation

It is important to note that FAFu is *not* a radio-coverage prediction tool. It is not intended to guarantee adequate performance of a CNPC link in the absence of interference. Each UAS will be responsible for keeping its transmitter power strong enough to satisfy its link budget, and its UA altitude high enough to keep the desired CNPC signal's radio line of sight (RLOS) to the ground station's radio antenna sufficiently clear of intervening terrain and other obstacles to ensure adequate coverage.

2.1 Frequency Requests

FAFu operation begins with a request, typically conveyed via the Internet or the FAA's System Wide Information Management (SWIM) capability, from the control element of a particular UAS for one or more CNPC frequencies to use during various phases of UA flight. (The entire flight may be treated as a single “phase” if the applicant so wishes.) To process requests for standalone CNPC links, FAFu needs the following information for each link and flight phase:

- The earliest possible start time and the estimated end time of the flight phase
- The horizontal limits and altitude ceiling of the service volume (SV) within which the UA will fly during the flight phase
- The latitude, longitude, site elevation, and antenna height of each ground station (GS) supporting the UAS
- The maximum gain, horizontal antenna pattern, polarization, and scan limits (if any) of each GS antenna
- The maximum gain and polarization of each UA antenna
- The output powers, occupied bandwidths, and emission masks of the GS and UA transmitters
- The selectivity masks or adjacent-channel rejection parameters of the GS and UA receivers
- Requested cochannel protection ratio (CCPR), which is the minimum acceptable ratio of desired-signal power to aggregate equivalent on-tune undesired-signal power under assumed free-space propagation conditions at the input of each of the GS and UA receivers belonging to the requesting UAS; typical values for this parameter are 25–35 decibels (dB)
- Receiver sensitivity, which FAFu requires to be at least 3 dB below the strength of the weakest signal expected to be received from the desired transmitter at the other end of the link, to leave sufficient margin for FAFu to use its frequency-assignment algorithms to cope with any undesired signals
- The tuning ranges and tuning increments of the GS and UA transmitters
- Whether the UAS’s CNPC uplink and downlink must have identical frequency assignments
- Any other CNPC link characteristics that are relevant to frequency selection.

A frequency request may be filed concurrently with, or after, the UAS flight plan. Much of the information listed above is ordinarily provided before the request or flight plan is filed. Antenna patterns, transmitter masks, and receiver masks are stored permanently in separate files within FAFu’s Equipment Type Characteristics (ETC) database. Whenever a user defines a new pattern or mask, FAFu assigns a unique numerical identifier to it so that subsequent applications involving the same antenna, transmitter, or receiver type can refer to that identifier and the user will not have to define the pattern or mask again.

FAFu provides users with on-line forms for entering input data for their frequency requests. The forms are designed to minimize unnecessary repetition in the data-entry process. Drop-down menus enable users to select pattern and mask identifiers from previously stored lists. Provision is made for easy entry of data on recurring operations. The forms also contain error traps (with easily comprehensible error messages) to prevent users from entering meaningless data such as negative bandwidths, nonexistent latitudes, or letters in numeric fields.

2.2 Frequency Searches

In processing each incoming frequency request, FAFu systematically searches for a frequency that can be assigned to the new CNPC link, without causing RFI between the new link and any preexisting terrestrial CNPC links (or other RF systems, in the same or adjacent frequency bands) that are identified in FAFu's Preexisting Assignments file as being active or potentially active during the time frame of the request. ("Other RF systems" may include navigational aids (navaids), non-CNPC radio links, CNPC links using satellite communications, and/or terrestrial networks that serve CNPC links but have not received frequency-block allotments from FAFu.)

The requesting UAS must provide lists of assignable frequencies for its CNPC uplinks and downlinks, together with the widths of the channels that are to be centered on each link's frequency once it is assigned. DO-362 stipulates that the lower end, the upper end, and the width of each CNPC channel must be integer multiples of 5 kilohertz (kHz) and that, consequently, each assignable frequency must be an integer multiple of 2.5 kHz.

2.2.1 Screening for Single-Interference Cases

FAFu begins the assignment search by using GS antenna locations, UA SV descriptions, and topographic information to identify every potential interference case in which an undesired signal could propagate between the applicant's GS or UA and a preexisting UAS's GS or UA, or between the applicant's GS or UA and any preexisting non-UAS RF equipment that might become a source or victim of RFI. However, in most cases where the applicant and a preexisting CNPC link are both using synchronized time-division duplexing (TDD), as stipulated in DO-362, FAFu considers only the UA-to-GS and GS-to-UA paths. UA-to-UA and GS-to-GS RFI cannot occur in such cases unless the path of the undesired signal is exceptionally long.

For each case identified, FAFu uses the GS locations, SV descriptions, and antenna information to calculate the worst-case (maximum) value of combined antenna gain (the sum of the gains of the antennas of the undesired transmitter and the victim receiver) in each direction along the potential interference path. The program also computes the frequency-dependent rejection (FDR) of the potential interference source/victim pair as a function of the difference between their tuned frequencies. Taking the combined antenna gain and calculated FDR curve into account, together with the output powers of the desired and undesired transmitters and the requested protection ratio or interference threshold of the potential victim receiver, FAFu uses the results of those calculations to compute a minimum allowable frequency separation (MAFS) between the new CNPC link and the other CNPC link or RF system currently under consideration. FAFu then removes, from the new link's list of candidate frequencies, any frequency that is separated by less than the MAFS from the frequency of the preexisting link or system. After all preexisting assignments have been considered in this manner, a subset of the original frequency list is typically still available for potential assignment to the new link. All these surviving candidate frequencies have been subjected to "one-on-one" interference analysis as described above, and so are all presumed free of RFI problems caused by transmitters acting separately.

2.2.2 Screening for Multiple-Interference Cases

However, it may still be possible for the combined effects of multiple transmitters using those surviving candidate frequencies to result in RFI. Multiple-interference effects are of two principal kinds: additive effects and intermodulation (IM). Additive interference results from the existence of multiple interference sources whose emissions overlap in frequency and, in combination, exceed the CCPR or RFI threshold of a potential victim receiver. IM interference can arise when the sums or differences of certain harmonics of ground radios (GRs) in a small geographical area are too close to the frequencies of UA in the vicinity. To protect against those possible RFI mechanisms, FAFu subjects each of the surviving candidate frequencies in turn to "many-on-one" additive and IM interference analyses (considering the impacts of multiple interferers on the new and preexisting links) until it finds one that does not result in interference.

2.3 Management Decisions and Interventions

As soon as a frequency passes all the above tests, FAFu recommends to the FAFu manager that the frequency be assigned to the new CNPC link. The manager then has the option of visually verifying the suitability of the proposed frequency assignment with the aid of FAFu's geographical/spectral map-display features and its various related interactive analytical capabilities. If the manager accepts FAFu's recommendation (as is ordinarily the case) or for some reason decides to assign an alternative frequency instead, then FAFu grants permission to the applicant, via the Internet, to operate on the assigned frequency under the conditions the applicant stipulated when making the request. The assignment message also informs the applicant of any "exclusion zones" (e.g., spheres of specified radius such as 500 feet) that its UA must observe around the GSs of other UAS to avoid mutual RFI resulting from transmitter noise that cannot be controlled by frequency restrictions alone. The frequency assignment becomes effective at the stipulated start time and remains in effect until the applicant sends FAFu a message releasing the frequency. (For reasons of safety, the assignment does *not* automatically expire at the estimated end time of the flight phase.)

If no candidate frequency survives all the tests, FAFu will so inform the manager, who may then deny the applicant's request for a frequency or, alternatively, may intervene by performing a FAFu-aided interactive analysis to identify opportunities for changing the situation to allow the applicant's request to be met. Such a change might consist of one or more of the following:

- Terminating assignments previously made to UAS that have kept frequency assignments past their estimated end times
- Relocating the GS of the requesting UAS
- Lowering the ceiling or horizontal extent of the requesting UAS's SV
- Reducing the transmitter power of the requesting UAS's GS or UA
- Changing one or more preexisting UAS assignments in a manner that would create spectral "room" for the new UAS's CNPC link.

If FAFu can identify such an opportunity, it notifies the manager, supporting its findings by means of map displays and reports. The manager may then contact the party or parties involved to ask whether they are amenable to the proposed changes. If all parties agree, then the manager grants permission to the applicant to use the newly approved frequency, and directs the timely retuning of any other CNPC links whose operators have agreed to change their frequencies.

2.4 Interference Reports

FAFu provides a mechanism for collecting, correlating, and responding to reports of interference from UAS and other users of the same and adjacent frequency bands. RFI reports may be filed via the Internet or SWIM. They must identify the frequencies affected, the times when interference events occur, the symptoms of the interference, and any other information that may help to pinpoint the source. If multiple RFI reports arrive, FAFu takes note of whether they are correlated in frequency, space, and/or time. FAFu displays the results in graphical form and, if it can, identifies possible causes, such as continued use of a frequency after it was released. The manager takes corrective action, such as contacting the control element of any UAS that appears to be an interference source, to resolve each case of reported interference as fast as possible. If a case cannot be resolved quickly, the manager reports it to enforcement authorities such as the Federal Communications Commission.

2.5 Evolution of the FAFu Manager's Role

The role of the human FAFu manager will evolve over time. When FAFu first becomes operational, assignment requests will arrive relatively infrequently, giving the manager significant time to resolve any procedural problems and to apply workarounds to problems that may arise within FAFu itself. As time passes, such problems will occur much less often, confidence in the system will rise, and the manager can devote less time to each incoming request. Eventually, managerial involvement will become unnecessary for routine assignment requests. In the end state, the manager will need to intervene only in emergencies (e.g., when interference is reported on an assigned frequency).

2.6 Other Functions

2.6.1 Archiving

FAFu routinely archives time-stamped records of all UAS frequency requests, FAFu frequency recommendations, manager interventions, actual frequency assignments, frequency releases, interference reports, and other significant transactions. These records are preserved for future replay, analysis, accounting, training, and other appropriate purposes.

2.6.2 Administrative Functions

FAFu provides the auditing and accounting branches of the CSA with data needed to perform their functions. FAFu depends on other administrative functions for its successful operation.

Auditing: The auditing function consists of monitoring usage of CNPC frequency resources throughout U.S. airspace to ascertain whether, where, and how much of the time each part of the spectrum is being used. The manager is able to view spectrum availability and congestion on a nationwide, regional, or local basis, as circumstances require. Cases of unauthorized use are referred to appropriate enforcement authorities, even if no interference has been reported. Cases of non-use of assigned spectrum are also noted, and users are advised to release spectrum that is seriously underutilized.

Accounting: The accounting function involves keeping track of each UAS's cumulative use of spectrum. No generally accepted measure currently exists for spectrum usage. A possible metric for the spectrum "consumed" by a single assignment might be a function of:

- Assignment duration (from the requested start time to the actual time when the frequency is released);
- The user-specified channel width;

- The proportion of each TDD frame used for the assignment (so that an uplink-only or downlink-only frequency might cost only half as much as a frequency used for both uplink and downlink); and
- The SV ceiling altitude of the requesting UAS (since a high-altitude UA has longer RLOSs to potential interference sources and victims than a low-altitude one, and consequently "ties up" its assigned frequency throughout a larger geographical area).

Other considerations may include:

- The CCPR stipulated by the user when requesting the assignment (since maintaining a higher protection ratio tends to reduce the pool of frequencies that neighboring UAS can use); and
- Overall demand for spectrum during the time window when the assignment is in effect.

A key issue yet to be resolved is whether the CSA will be allowed to bill each UAS operator according to its cumulative spectrum usage, calculated in accordance with whatever metric is chosen. It is likely that Congressional authorization would be required for this.

Support Functions: Certain other CSA administrative functions play a role in supporting FAFu. These include technical support for FAFu hardware and software, and renewal of licenses for the topographic database.

3 The Interference Model

FAFu models the electromagnetic interactions in a user-defined environment comprising multiple air/ground (A/G) radios. (The term “radio” is construed here to encompass not only equipment used for CNPC or other communications purposes, but also other RF devices such as navaids that could be involved in frequency-dependent interference interactions with CNPC radios.) Each radio comprises one or two equipments, of which there are three types: transmitters, receivers, and transceivers. A transceiver is an equipment that can alternately transmit and receive on a single frequency.

The terms “radio” and “equipment,” as used in this model, are understood to refer to functional or logical entities, not necessarily to single pieces of physical hardware. It is quite possible for a ground-based transmitter and receiver to belong to the same “radio” without sharing the same case or even the same building. Similarly, a “transceiver”—a single logical equipment in this model—could comprise two physically separate though collocated pieces of hardware that take turns transmitting and receiving on a common frequency.

In this model, the location of a radio (and its equipments) in the environmental database is treated as being identical to the physical location of its antenna. The fact that some actual radios may be separated from their antennas by several hundred feet of cable generally does not have a significant effect on frequency management, and so is not considered here.

3.1 Radio Links

Each radio in the environment belongs to an A/G radio link, of which Figure 3-1 depicts an example. Data messages traverse the desired signal path in both directions between the link’s GR and its airborne radio (AR).

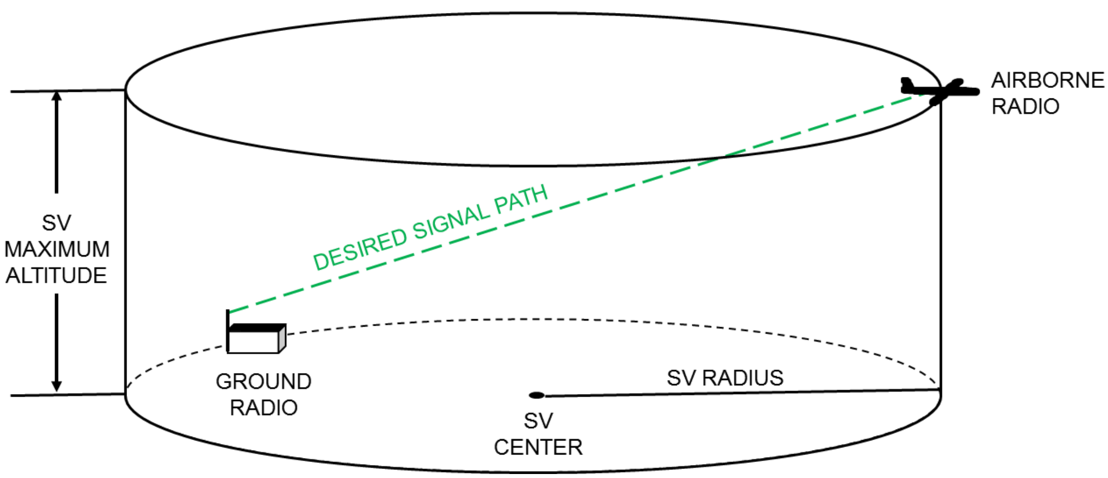


Figure 3-1. An Air/Ground Radio Link

A link in this model usually represents a fixed-position GR and an AR aboard a UA operated by a pilot in a defined SV. A GR can be a transmitter, a receiver, or a transceiver. The same is true of an AR. The model assumes that the AR’s position varies freely throughout the SV. This assumption is appropriate for frequency-planning purposes, since worst-case positions—those tending to maximize the severity of RFI when it occurs—are generally assumed for the AR whenever the model computes the length of a desired or undesired signal path.

The link of Figure 3-1 has a circular SV (CSV) with a circular horizontal cross section. Such an SV is fully defined by the SV radius in nautical miles (nmi), the SV ceiling in feet, and the latitude and longitude of the SV center. The GR is not necessarily located at the SV center, and may lie outside the SV. Not all SVs have circular cross sections; in some cases, their cross sections are polygonal. In some situations, an SV may be so large, or so fragmented by terrain features that block radio-wave propagation, that two or more GRs are needed at widely separated sites to ensure reliable communication throughout the SV. Such GRs might be selectively keyed by the pilot, who could operate whichever GR happens to be best situated to reach the UA.

An A/G link in the FAFu environment may be designated as single-frequency bidirectional or dual-frequency. In a *single-frequency bidirectional* pair, the AR consists of a single equipment (a transceiver) that needs only one frequency to participate in a given two-way A/G radio link alternating between ground-to-air and air-to-ground operation. However, the *ground* radio in a single-frequency bidirectional pair may be a transceiver, transmitter, or receiver. This flexibility enables a FAFu environmental database to model situations where a particular two-way link's ground-based transmitting and receiving antennas are at different locations, identified in separate records in the database. For brevity, single-frequency bidirectional pairs are sometimes simply called "single-frequency" (SF) pairs in this report.

Each radio in a *dual-frequency* (DF) pair contains two equipments: a transmitter and a receiver operating simultaneously on separate uplink and downlink frequencies.

3.2 Interference Between Radio Links

Figure 3-2 depicts an example of one A/G radio link potentially inflicting RFI on another. The potential victim or "subject" AR receives not only the desired signal from its own GR, but also an undesired signal transmitted by the other GR, whose AR occupies a separate SV in the vicinity. This is a case of potential "ground-to-air" RFI that FAFu must prevent by appropriately assigning frequencies to the two links. The subject GR, of course, can also interfere with the other AR, and FAFu must deal with that possibility as well. FAFu can also check for ground-to-ground, air-to-ground, and air-to-air RFI cases not shown in Figure 3-2.

The necessary CCPR for any given A/G radio link can be identified on the basis of the link's power budget and the RF characteristics of the radios. The CCPR is the minimum power advantage (in dB) that the desired signal must have over the undesired signal, after taking into account the FDR of the undesired signal as a result of separating the two links in frequency, to:

- Overcome intermittent signal fading that may result from UA airframe shadowing, multipath effects, and/or rain losses; and
- Provide the additional "aviation safety margin," usually considered to be 6 dB, that the International Civil Aviation Organization (ICAO) advocates for safety-critical aeronautical radio links.

If all the radios in the band had identical output powers and equal-gain omnidirectional antennas, then over a smooth earth in free-space loss conditions the required frequency separation could be determined by the expression

$$F^{-1}(C - 20\log(D_u/D_d)) \tag{3-1}$$

where

C = CCPR

$F(\Delta f)$ = FDR, in dB, of a signal centered Δf frequency units from the receiver frequency

$F^{-1}()$ is the inverse function of $F(\Delta f)$ and has units of frequency

D_u and D_d are undesired and desired signal-path lengths, respectively.

Under those conditions the requirements for maintaining adequate CCPRs could be expressed as a MAFS curve like the one shown at the bottom of Figure 3-2.

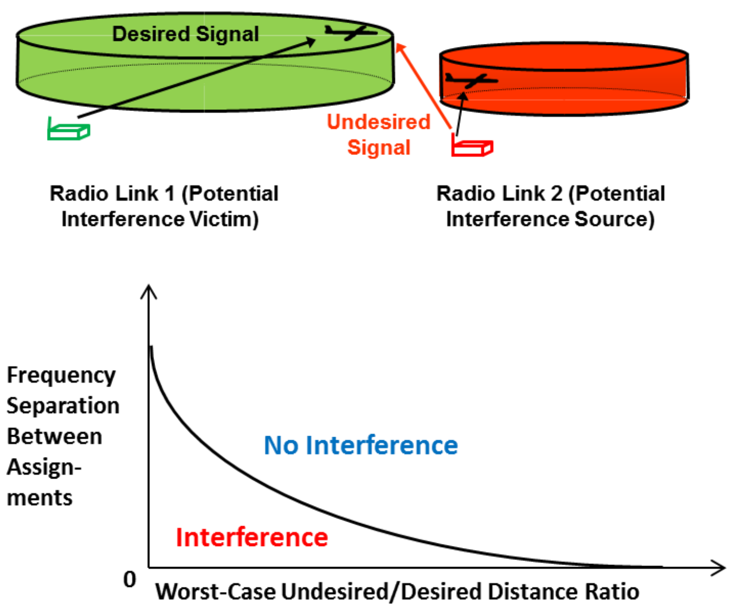


Figure 3-2. Preventing Potential RFI Between Two Radio Links

However, the actual CNPC radio environment will be considerably more complex than the simple curve in Figure 3-2 implies. Complicating factors include:

- Time-division duplexing
- Horizon and terrain shielding
- Atmospheric refraction
- Unequal transmitter powers
- Unequal antenna gains.

These issues are considered in the following subsections.

3.3 Time-Division Duplexing

CNPC radios built in accordance with DO-362 must utilize the TDD frame structure illustrated in Figure 3-3. This common frame structure, together with DO-362's associated requirement for universal TDD synchronization with a timing accuracy of one microsecond, precludes nearly all cases of ground-to-ground RFI and most cases of air-to-air RFI among radios complying with the standard.

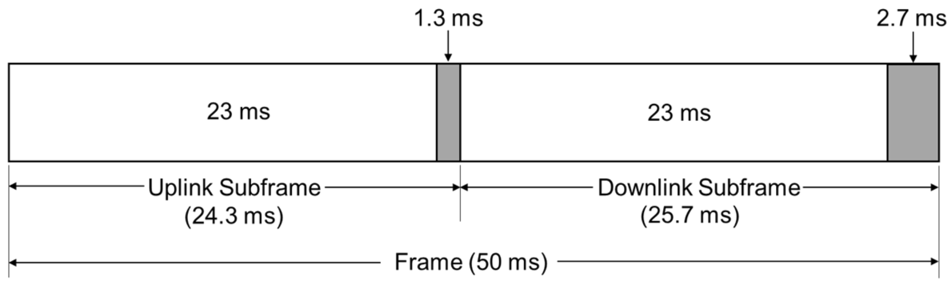


Figure 3-3. DO-362 TDD Frame Structure

Since radio signals travel at 161.875 nmi per millisecond (ms), the 1.3-ms uplink guard time protects DO-362-compliant GRs against delayed arrival of each other's potentially interfering signals (ground-to-ground RFI) unless the undesired signal path length exceeds that of the desired signal by more than (1.3) (161.875) = 210 nmi. Similarly, the 2.7-ms downlink guard time protects compliant ARs against mutual air-to-air RFI unless an undesired transmitter is at least (2.7) (161.875) = 437 nmi farther away than the desired transmitter. At such long distances the undesired signal is usually beyond RLOS or attenuated too much by distance to cause RFI. However, ground-to-ground and air-to-air RFI can still easily occur when a nearby potential source or victim of RFI is a navaid or other system that operates in the same frequency band as a DO-362 radio but does *not* comply with DO-362.

3.4 Blocking of Undesired Signals by the Earth

The possibility of RFI between two radio links operating in ultrahigh-frequency (UHF) or superhigh-frequency (SHF) bands is greatly reduced if every possible RLOS between them is blocked by the curvature of the earth or by terrain. In very high frequency (VHF) and sometimes in UHF bands, A/G radio spectrum-management calculations often assume a smooth earth with a radius that is 4/3 (or some other factor greater than one) times that of the actual earth, to allow for downward ray-bending resulting from variation of atmospheric refractivity with height.

If a 4/3 earth is assumed, the maximum unobstructed RLOS distance (in nmi) between two ground-based or airborne antennas H_1 and H_2 feet off the ground, respectively, is $1.23\left(\sqrt{H_1} + \sqrt{H_2}\right)$. (Since the smooth-earth radio-horizon distance varies as $\sqrt{K}$, where K is the assumed effective-earth-radius ratio [4, p. 820], the factor 1.23 may be replaced by $1.0652\sqrt{K}$ if a value of K other than 4/3 is assumed.) In the example of Figure 3-4, the subject SV is protected by the radio horizon from the "hidden" SVs but could still be involved in interference with the "partially visible" SV. A transmitter in that SV could be above the earth-grazing RLOS shown in the figure, and thus could have an unobstructed RLOS to a receiver in the subject SV.

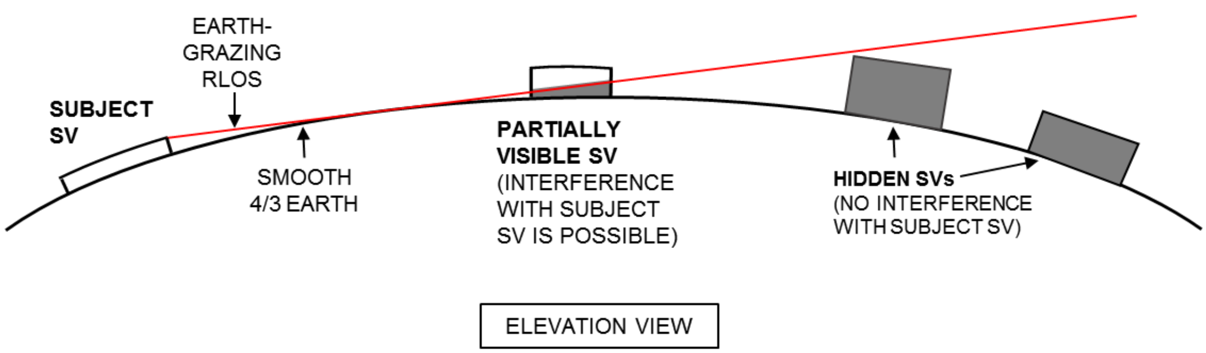


Figure 3-4. Horizon Shielding by a Smooth Earth

In many places, of course, the earth is not even approximately smooth. Using a topographic database in a situation like that of Figure 3-4 might reveal, for example, that the "partially visible" SV is actually not visible at all from any part of the subject SV. Since shadowing effects become more pronounced at higher frequencies, the use of a terrain database in FAFu is important in the 960–1164 MHz band and even more so in the 5030–5091 MHz band for locating the actual horizon of a transmitter or receiver. Figure 3-5 illustrates this for a case in which terrain protects a low-flying UA against undesired signals from a distant ground transmitter, but does not provide protection when the UA flies higher.

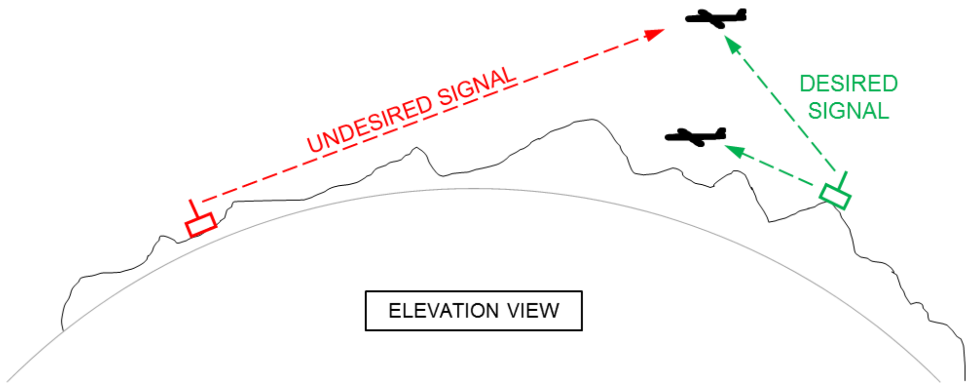


Figure 3-5. Terrain Shielding

3.5 Computing MAFS over Rough Earth When Link Characteristics Differ

FAFu considers the effective isotropically radiated powers (EIRPs) of desired and undesired transmitters when calculating MAFS values. An EIRP is a transmitter's actual power in dB referred to one milliwatt (dBm), plus its antenna's maximum gain in dB referred to the gain of a lossless isotropic antenna (dBi). FAFu calculates the EIRP of each GR and AR as the sum of its power and the maximum gain of its transmitting antenna.

FAFu also considers undesired-signal propagation via diffraction paths over rough terrain. However, it is very important to note that FAFu takes rough-earth signal blockages and non-free-space losses into account only for *undesired* signals, and not for desired signals. FAFu is not a wireless coverage analysis tool. Instead, FAFu assumes that every UA will fly high enough within its SV to ensure that the *desired* signal's RLOS clearance above terrain will be sufficient (i.e., at least 60 percent of the first Fresnel zone's radius) to keep its diffraction losses negligible. The desired signal is, of course, highly susceptible to multipath fading, but a well-chosen value of CCPR can provide the link budget with sufficient margin to prevent such fading from excessively degrading link availability.

MAFS calculations are of two kinds: ratio-based and distance-based. FAFu can perform either type of calculation whenever warranted by circumstances. The two types of calculations are discussed separately below.

3.5.1 Ratio-Based MAFS Calculations

The ratio-based approach is useful in "interference-limited" environments or systems. It is intended to guarantee that, in situations involving a single undesired signal, the effective desired-to-undesired signal-power ratio at the input to a receiver (or, equivalently, the effective undesired-to-desired path-length ratio) will not fall below a certain value. FAFu always uses the ratio-based approach when the receiver to be protected against RFI belongs to a CNPC link.

Figure 3-6 depicts the classic "interference triangle" comprising the desired transmitter T_d, the undesired transmitter T_u, the potential victim receiver R upon which the desired and undesired signals impinge, and the relevant RF parameters associated with both signals. T_d, T_u, and R can be airborne or ground-based. But when the desired link is an A/G radio system, R must be ground-based if T_d is airborne, or airborne if T_d is ground-based.

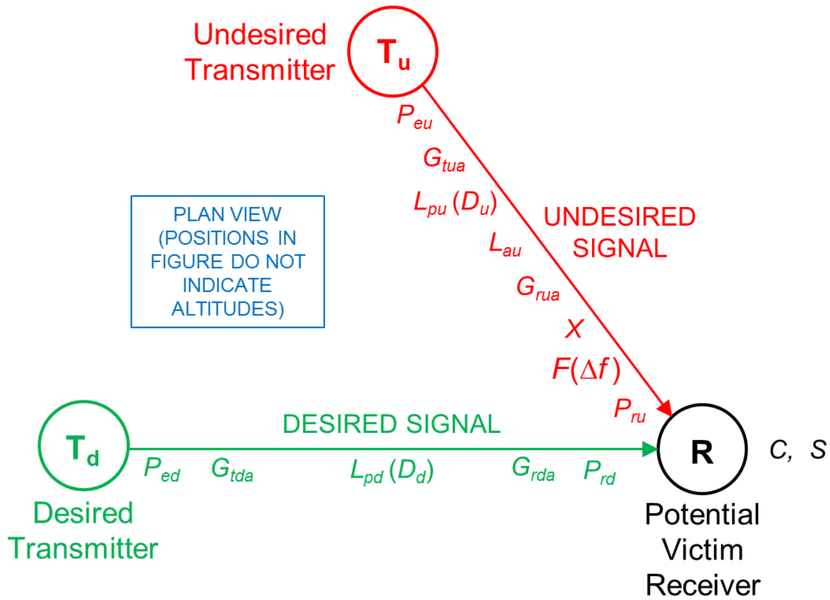


Figure 3-6. Ratio-Based MAFS Scenario

The received desired and undesired signals may be expressed as

$$P_{rd} = P_{ed} - G_{tda} - L_{pd}(D_d) + G_{rmax} - G_{rda} \tag{3-2}$$

$$P_{ru} = P_{eu} - G_{tua} - L_{pu}(D_u) - L_{au}(T_{pc}) + G_{rmax} - G_{rua} - X - F(\Delta f) \tag{3-3}$$

$$L_{pd}(D_d) = 20\log f_d + 20\log D_d + 37.8 \tag{3-4}$$

$$L_{pu}(D_u) = 20\log f_u + 20\log D_u + 37.8 \tag{3-5}$$

where

P_{rd} = desired-signal power, in dBm, at input to receiver R

P_{ru} = effective on-tune undesired-signal power, in dBm, at input to receiver R

P_{ed} = EIRP in dBm of desired transmitter T_d, which can be ground-based or airborne

P_{eu} = EIRP in dBm of undesired transmitter T_u, which can also be ground-based or airborne

G_{tda} = off-axis attenuation, in dB, of T_d's antenna gain in direction toward R

G_{tua} = off-axis attenuation, in dB, of T_u's antenna gain in direction toward R

L_{pd} (D_d) = desired signal's free-space loss in dB along desired path D_d nmi long

L_{pu} (D_u) = undesired signal's free-space loss in dB along undesired path D_u nmi long

L_{au} (T_{pc}) = additional undesired-signal path-loss value (dB) that equals or exceeds the actual value during T_{pc} percent of the time in an average year

f_d = carrier frequency of desired signal (i.e., its channel center frequency), in MHz

f_u = carrier frequency of undesired signal (its channel center frequency), in MHz

G_{rmax} = maximum gain, in dBi, of receiver R's antenna

G_{rda} = off-axis attenuation, in dB, of R's antenna gain in direction toward T_d

G_{rua} = off-axis attenuation, in dB, of R's antenna gain in direction toward T_u

X = cross-polarization discrimination by R's antenna, in dB, against undesired signal

$F(\Delta f)$ = the receiver's FDR, in dB, of the undesired signal as a function of Δf

Δf = frequency offset, in kHz, of undesired- and desired-signal carriers = $1000|f_u - f_d|$.

Time percentage T_{pc} is an important parameter for which FAFu uses the same value in processing all assignment requests. The FAFu manager sets T_{pc} in accordance with CSA policy. T_{pc} determines how cautious FAFu will be in assigning frequencies. If T_{pc} is set to, say, 0.2%, then FAFu is likely to overestimate undesired-signal path loss (and thus create a risk of RFI to the receiver) only about 0.2% of the time. A larger value of T_{pc} increases the risk of RFI; a lower value reduces the RFI risk, but is apt to rule out more candidate frequencies and so increases the chance that FAFu will fail to find *any* assignable frequency for the requester's CNPC link. Section 6 explains how FAFu calculates L_{au} as a function of T_{pc}.

When T_u or R is airborne, which is usually true of interference source/victim pairs in an air/ground radio system, multiple paths between T_u and R must be evaluated because of the mobility of the UA. If only one is airborne, as in the example of Figure 3-7, FAFu must draw radials between the GS of one UAS and the SV ceiling perimeter of the other. (The radials should be evenly spaced in azimuth as seen from the GR, ideally with an angular increment small enough to make the spacing of their respective intersections with the other link's SV comparable to the spacing of the gridpoints in the terrain database.) If T_u and R both are airborne, a much larger number of crossing paths (from points on T_u's SV perimeter to points on R's SV perimeter) must be evaluated. In such situations, L_{au} and P_{ru} must be computed for each of the paths, and the largest resulting value of P_{ru} is used in subsequent calculations.

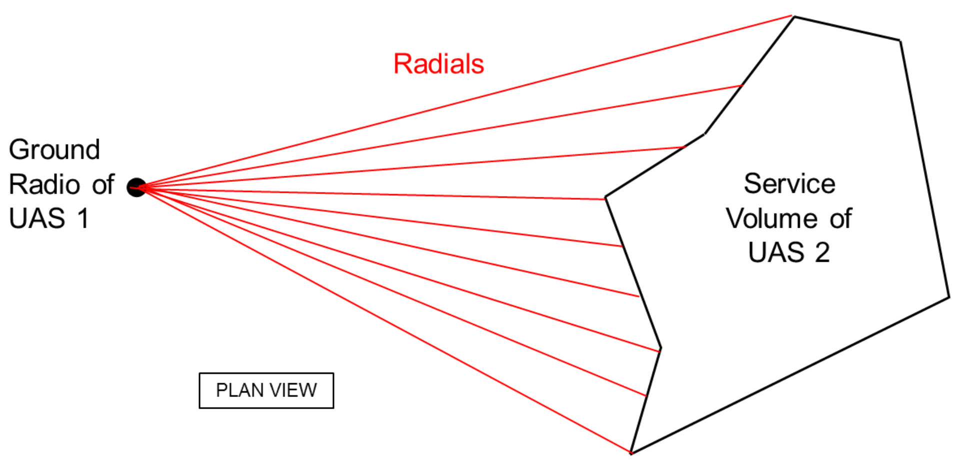


Figure 3-7. Multiple Propagation Paths Between One UAS's GR and Another's SV

An important user-defined parameter in ratio-based interference calculations is receiver sensitivity S, expressed in dBm. S generally means the lowest value of P_{rd} that allows the receiver to function reliably in the absence of interference. However, A/G radio link budgets are commonly designed to allow for an aggregate undesired-signal level equal to the noise power in the receiver, which effectively doubles the interference-plus-noise value and so adds 3 dB to the value of P_{rd} needed for reliable operation of the desired link. This requirement may be expressed as

$$P_{rd} \geq S + 3. \tag{3-6}$$

Another prerequisite for reliable link operation is

$$P_{rd} - P_{ru} \geq C, \tag{3-7}$$

where C is the CCPR, in dB.

Substituting (3-2) – (3-5) into (3-7) yields

$$(P_{ed} - P_{eu}) - (G_{tda} - G_{tua}) + 20\log(f_u/f_d) + 20\log(D_u/D_d) + L_{au}$$
$$-(G_{rda} - G_{rua}) + X + F(\Delta f) \geq C. \tag{3-8}$$

The frequency ranges currently being considered for use by DO-362-compliant CNPC links are so narrow that the 20 log (f_u / f_d) term can be ignored with relatively little loss of accuracy, so (3-8) becomes

$$(P_{ed} - P_{eu}) - (G_{tda} - G_{tua}) - (G_{rda} - G_{rua}) + L_{au} + X + 20\log(D_u/D_d)$$
$$+ F(\Delta f) \geq C, \tag{3-9}$$

and the MAFS, the minimum allowable value of Δf, is given by

$$F^{-1}\Big(C - \big((P_{ed} - P_{eu}) - (G_{tda} - G_{tua}) - (G_{rda} - G_{rua}) + L_{au} + X\big) - 20\log(D_u/D_d)\Big). \tag{3-10}$$

It is convenient to define a ratio-adjustment factor J_R that expresses the amount by which additional undesired-signal path losses, and differences between the EIRPs and antenna parameters associated with the desired and undesired signals, alter the minimum distance ratio that would otherwise be necessary for a given frequency offset. J_R is the factor by which (D_u / D_d)—the actual worst-case ratio of undesired-signal path length to desired-signal path length—should be multiplied to yield a ratio-based MAFS for a given source-victim equipment pair. We define J_R as

$$J_R \equiv \text{antilog}\Big(\big((P_{ed} - P_{eu}) - (G_{tda} - G_{tua}) - (G_{rda} - G_{rua}) + L_{au} + X\big)/20\Big), \tag{3-11}$$

and so the ratio-based MAFS may be expressed as

$$F^{-1}\Big(C - 20\log\big(J_R\,(D_u/D_d)\big)\Big). \tag{3-12}$$

If desired and undesired EIRPs and antenna gains are equal, and if there is no cross-polarization discrimination, then $J_R = 1$.

3.5.2 Distance-Based MAFS Calculations

A distance-based MAFS is useful in "noise-limited" environments or systems, and is meant to ensure that the effective undesired-signal power at the input to a receiver will not exceed a certain interference threshold T, expressed in dBm, regardless of how strong the desired signal may be. In such situations a prerequisite for reliable operation of the receiver is

$$P_{ru} \leq T. \tag{3-13}$$

FAFu always uses the distance-based approach when the receiver to be protected against RFI belongs to a navaid operating in the same band as the CNPC links.

When using a distance-based MAFS curve, the parameters of the *desired* link never come into play; only the *undesired* link needs to be considered. Thus there is no need to consider P_{ed}, or to calculate G_{tda} or G_{rda}. It is also unnecessary to consider P_{eu}, since there is no P_{ed} with which to compare it. That leaves only G_{tua}, G_{rua}, L_{au}, X, and L_{pu} (D_u) as relevant parameters, as shown in Figure 3-8.

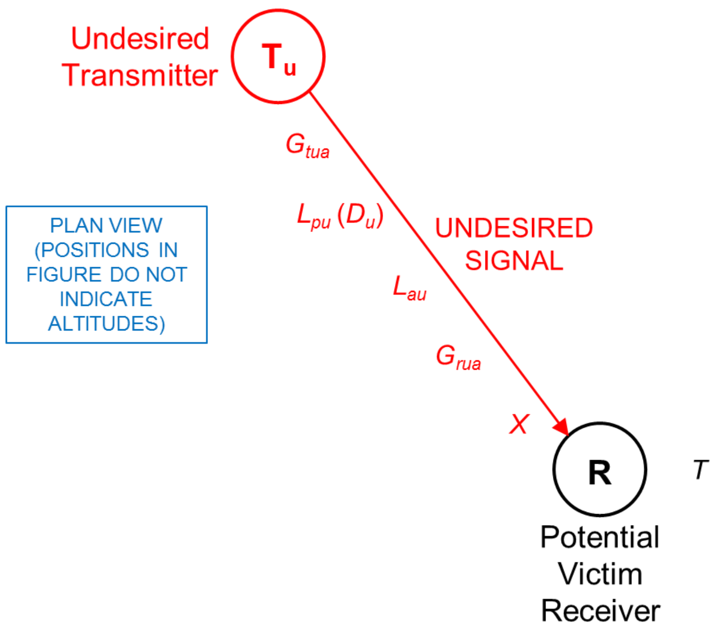


Figure 3-8. Distance-Based MAFS Scenario

Distance-based MAFS curves are often based on the case where the antennas of interfering transmitter T_u and victim receiver R are pointing directly toward each other (so $G_{tua} = G_{rua} = 0$) and have identical polarizations (so $X = 0$), and the only propagation loss experienced by the undesired signal is free-space loss L_{pu} (D_u). Such a curve defines the MAFS for every possible value of D_u on the basis of those assumptions, where $G_{tua} + G_{rua} + L_{au} + X = 0$. Because G_{tua}, G_{rua}, and X are always nonnegative, any nonzero value of any of them tends to *decrease* the minimum value of D_u needed to allow a given frequency offset between the carrier frequencies of T_u and R. (L_{au}, on the other hand, can be negative for small values of T_{pc}.) Since L_{pu} (D_u) varies as 20 log D_u, the resultant distance-adjustment factor J_D can be defined as follows:

$$20\log(J_D D_u) = 20\log D_u + G_{tua} + G_{rua} + L_{au}(T_{pc}) + X \qquad \text{(3-14)}$$

$$J_D \equiv \text{antilog}\Big(\big(G_{tua} + G_{rua} + L_{au}(T_{pc}) + X\big)/20\Big). \qquad \text{(3-15)}$$

Substituting (3-3), (3-5), and (3-15) into (3-13) yields the following expression for a distance-based MAFS that takes antenna patterns, polarizations, and additional path losses into account:

$$F^{-1}(P_{eu} + G_{rmax} - 37.8 - T - 20\log(f_u D_u J_D)). \qquad \text{(3-16)}$$

As with ratio-based MAFS calculations, multiple interference paths must be considered if T_u and/or R is airborne, and the one that yields the largest value of P_{ru} will become the basis of later calculations.

3.6 Multiple Interferers

Most incoming frequency requests require FAFu to deal with cases where receivers are subjected to two or more undesired signals simultaneously. After FAFu has separately considered each potential interferer or victim associated with a new frequency request, determined MAFS values as discussed in Section 3.5, and winnowed the requester's original list of candidate frequencies accordingly, it must consider the potential combined effects of multiple interferers on individual receivers.

FAFu checks for additive interference problems by making a trial assignment of each surviving candidate frequency in turn to the requester's CNPC link, and analyzing the potential impact of that assignment by applying expression (3-7) or (3-13), as appropriate, to every receiver belonging to the new CNPC link or to any preexisting link that could become a victim of interference from that new link. In each such analysis, P_{ru}, instead of representing the strength of one received undesired signal considered in isolation, is the summation of the effective on-tune received powers of all the undesired signals impinging on the receiver. Any resultant violation of any receiver's CCPR or interference threshold disqualifies the candidate frequency currently being considered.

Besides additive interference, multiple undesired signals can also create intermodulation products (IMPs) at frequencies that are the sums or differences of the fundamental frequencies and/or low-order harmonics of the separate undesired signals. An IMP whose frequency is too close to the tuned frequency of a nearby receiver can degrade that receiver's operation. If all the transmitters involved are DO-362-compliant, this is unlikely to happen, because DO-362's TDD scheme (Section 3.3) ensures that compliant ground transmitters will not operate during the same subframe as compliant ground receivers. But it can happen if navaids or other noncompliant transmitters are in the vicinity. If so, FAFu also checks for potentially interfering IMPs and deletes frequencies as appropriate from the list of candidates.

FAFu assigns to the requester's CNPC link the first candidate frequency it finds that survives all the multiple-interference tests. If no candidate frequency survives, FAFu looks for opportunities to resolve the problem by spectral repacking: i.e., changing the frequency of one or more preexisting links in a way that will create spectral room for the new link. If FAFu finds any such opportunity, it notifies the FAFu manager, who can then decide whether to pursue it by seeking permission from the users of the preexisting links that would be affected.

4 Frequency-Dependent Rejection

FDR is the attenuation of a radio signal that occurs within a radio receiver because of an offset between the carrier frequency of the signal and the tuned frequency of the receiver, and/or a mismatch between the bandwidths of the signal and the receiver. To calculate a ratio-based MAFS in accordance with equation (3-12) in Section 3.5.1, FAFu must be capable of evaluating the FDR function $F(\Delta f)$ and its inverse. This section describes methods for doing so. The procedures depend on whether the transmitter and receiver under consideration are both compliant with RTCA DO-362 [1].

4.1 When the Transmitter and Receiver Both Comply with DO-362

FDR is not mentioned explicitly in the normative part of DO-362. However, when the undesired transmitter and the potential victim receiver are both DO-362-compliant, the adjacent-channel rejection (ACR) and non-adjacent-channel rejection (NACR) requirements in that standard may be used as a basis for algorithms to determine FDR. The ACR and NACR test requirements defined in DO-362 Section 2.2.1.7 may be paraphrased as follows:

1. A CNPC receiver shall operate satisfactorily when $P_{rd} = S + 3$, $P_{ru0} = P_{rd} + 19$, and $\Delta f = 0.5\ (C_D + C_U)$, where $P_{ru0} = P_{ru} + F(\Delta f)$ (i.e., the received undesired signal in dBm, *without* FDR subtracted from it); P_{rd}, P_{ru}, and S (all in dBm) are defined as in Section 3 of this (FAFu) report; Δf is absolute frequency difference in kilohertz between the carriers of the desired and undesired links; and C_D and C_U are the respective channel widths in kilohertz of the desired and undesired links. (This value of Δf puts the undesired signal at the smallest possible "adjacent-channel" frequency separation from the desired signal's center frequency.)
2. A 960–1164 MHz CNPC receiver shall operate satisfactorily when $P_{rd} = S + 3$, $P_{ru0} = P_{rd} + 54$, and $\Delta f = \max\ (0.5\ (3.5C_D + C_U), 0.5\ (C_D + 3.5C_U))$. (In this frequency band, this value of Δf puts the undesired signal at the smallest possible "non-adjacent-channel" (i.e., beyond-adjacent-channel) frequency separation from the desired signal's center frequency.)
3. A 5030–5091 MHz CNPC receiver shall operate satisfactorily when $P_{rd} = S + 3$, $P_{ru0} = P_{rd} + 44$, and $\Delta f = \max\ (0.5\ (2C_D + C_U), 0.5\ (C_D + 2C_U))$. This value of Δf puts the undesired signal at the smallest possible beyond-adjacent-channel frequency separation for this frequency band.
4. A 5030–5091 MHz CNPC receiver shall also operate satisfactorily in the strong-undesired-signal case where $P_{ru0} = –38$, $P_{rd} = P_{ru0} – 44$, and $\Delta f = \max\ (0.5\ (2C_D + C_U), 0.5\ (C_D + 2C_U))$—that is, the smallest possible beyond-adjacent-channel separation for this band.

For the *cochannel* interference case, in which $\Delta f < 0.5\ (C_D + C_U)$, the link budgets in DO-362 Appendix L require P_{rd} to exceed the sum of received interference and noise by at least 4.5 dB. Given the conservative assumption that the interference and noise powers are equal so that interference and noise are each 3 dB less than their sum, this indicates that when $\Delta f = 0$ the receiver can operate satisfactorily if P_{rd} exceeds P_{ru0} by at least 7.5 dB. It follows from this and from the foregoing ACR and NACR test criteria that, if $P_{rd} = S + 3$ and (in the 5030–5091 MHz band) $P_{ru0} \leq –38$, then:

- An undesired CNPC signal in an adjacent channel has to be (7.5 + 19) = 26.5 dB stronger than a cochannel undesired CNPC signal to cause interference to the victim CNPC link. In other words, the CNPC receiver's FDR of an adjacent-channel undesired CNPC signal is 26.5 dB.
- Similarly, a 960–1164 MHz CNPC receiver's FDR of a beyond-adjacent-channel undesired CNPC signal is (7.5 + 54) = 61.5 dB.
- A 5030–5091 MHz CNPC receiver's FDR of a beyond-adjacent-channel undesired CNPC signal is (7.5 + 44) = 51.5 dB.

The FDR rules for pairs of DO-362-compliant CNPC links are summarized below in a form suitable for their incorporation into FAFu. It is assumed that, as stipulated in [1, para. 2.2.1.6.2], the channel widths and masks of the desired and undesired links have been made wide enough to allow for the worst-case potential effects of Doppler shifts that could result from platform motion, and also for differences between assigned and actual carrier frequencies that could arise from frequency inaccuracies in the transmitters or receivers themselves.

4.1.1 960–1164 MHz Band

If the two DO-362-compliant CNPC links are in the 960–1164 MHz band and $P_{rd} \geq S + 3$, then

$$\begin{aligned} F(\Delta f) &= 0 \text{ dB if } 0 \leq \Delta f < 0.5\,(C_D + C_U) \\ &= 26.5 \text{ dB if } 0.5\,(C_D + C_U) \leq \Delta f < \max\,(0.5\,(3.5C_D + C_U),\, 0.5\,(C_D + 3.5C_U)) \\ &= 61.5 \text{ dB if } \Delta f \geq \max\,(0.5\,(3.5C_D + C_U),\, 0.5\,(C_D + 3.5C_U)). \end{aligned} \tag{4-1}$$

If $P_{rd} < S + 3$, no reliable FDR value can be found, and FAFu will advise the requesting UAS to modify its input link parameters to allow P_{rd} to be at least equal to $S + 3$ so that the link can be assigned a frequency.

4.1.2 5030–5091 MHz Band

If the compliant links are in the 5030–5091 MHz band, and if $P_{rd} \geq S + 3$ and $P_{ru0} \leq -38$, then

$$\begin{aligned} F(\Delta f) &= 0 \text{ dB if } 0 \leq \Delta f < 0.5\,(C_D + C_U) \\ &= 26.5 \text{ dB if } 0.5\,(C_D + C_U) \leq \Delta f < \max\,(0.5\,(2C_D + C_U),\, 0.5\,(C_D + 2C_U)) \\ &= 51.5 \text{ dB if } \Delta f \geq \max\,(0.5\,(2C_D + C_U),\, 0.5\,(C_D + 2C_U)). \end{aligned} \tag{4-2}$$

If $P_{rd} < S + 3$, FAFu will advise the requesting UAS to modify its input link parameters. If $P_{ru0} > -38$, FAFu will make the frequency assignment conditional on keeping the receiver outside an appropriately sized exclusion zone around the undesired transmitter, so that the worst-case P_{ru0} will be reduced to –38 dBm or less.

4.2 When the Transmitter or Receiver Is Noncompliant with DO-362

In some cases, the transmitter, the receiver, or both may be noncompliant with DO-362. This would be the case if the potential RFI source or victim radio were a terminal of an in-band navigation system such as Distance Measuring Equipment (DME) or the Microwave Landing System (MLS). It might also happen if regulatory authorities allowed some noncompliant CNPC radios to operate in the band. In such cases FDR criteria must be determined either by measurement or by analysis, and stored in FAFu's ETC database for future reference.

4.2.1 Experimental Determination of FDR

For specific pairs of equipment types, $F(\Delta f)$ can be determined experimentally by simultaneously subjecting a sample receiver to a desired signal of a particular strength (P_{rd}) and an undesired signal at various values of P_{ru0} and Δf. The outcome of the test will be a curve showing the maximum value of undesired-signal strength that the receiver can tolerate for each tested value of frequency offset. Depending on the receiver type and the way the test was conducted, the value of the curve at Δf = 0 kHz will be a protection ratio (CCPR) in decibels or an interference threshold (T) in dBm. Normalizing the data to 0 dB at Δf = 0 kHz will turn it into a curve of $F(\Delta f)$ for every tested value of Δf. The FAA is currently conducting tests of this kind to determine the FDR curves and susceptibility thresholds of certain types of 960–1164 MHz navigation and surveillance receivers, with a DO-362-formatted RF signal playing the role of potential interferer.

4.2.2 Analytical Determination of FDR

If adequate experimental data are unavailable but spectral masks are available for both the transmitter and the receiver, the FDR can be computed [5] from those masks as

$$F(\Delta f) = 10 \log \frac{\int_{-\infty}^{\infty} s(f) df}{\int_{-\infty}^{\infty} s(f) r(f + \Delta f) df} \tag{4-3}$$

where

$s(f)$ is the transmitter mask (power spectral density in linear units, normalized to a maximum value of 1, as a function of absolute frequency difference f from the transmitter's tuned frequency)

$r(f)$ is the receiver mask (squared magnitude of the receiver's frequency response in linear units, normalized to a maximum of 1, as a function of absolute frequency difference f from the receiver's tuned frequency).

The same frequency units must be used for f in both integrals, and also for Δf.

Transmitter and receiver masks are ordinarily expressed and depicted in logarithmic form (i.e., in decibels) as follows:

$$S(f) = 10 \log s(f) \tag{4-4}$$

$$R(f) = 10 \log r(f) \tag{4-5}$$

However, the FAFu user will specify mask values not in that form but instead as decibels of *attenuation* relative to maximum values, i.e., $(S(f))_{max} - S(f)$ and $(R(f))_{max} - R(f)$. In this form, the ordinate values are always nonnegative.

Since FAFu transmitter and receiver masks have the same form, only one "spectral mask" file format is needed to store them. Any given spectral mask can be referenced as a transmitter and/or receiver mask, even in the same frequency-assignment request. These masks will always be symmetric with respect to f = 0, so only the right side (the side with nonnegative frequency differences from the channel center frequency) needs to be entered.

The first point in any FAFu transmitter or receiver mask must be for a frequency difference of zero. The points in the mask must be entered in ascending order of absolute frequency difference. The attenuation must monotonically increase with increasing difference from the channel center frequency. The program automatically fills in the left side, which will be the mirror image of the right side. For all values of frequency difference greater than the final value entered by the user, the program assumes constant attenuation, resulting in a final “floor” value of *s*(*f*) or *r*(*f*). The value of *f* chosen for the final point should be large enough to ensure that the calculation will consider the noise floor of the transmitter or response floor of the receiver throughout the device’s operating frequency range (e.g., 5030–5091 MHz).

Each spectral-mask record must contain:

- Mask number allowing FAFu to look up the mask later in its ETC database
- Number of points specified on right side of mask
- Coordinates of first point

  ...

- Coordinates of last point.

Each point specified in the record has two coordinates:

- Difference from center frequency (zero for first point, monotonically increasing thereafter)
- Attenuation in decibels (zero at first point, monotonically increasing thereafter).

Figure 4-1 shows an example of a transmitter mask.

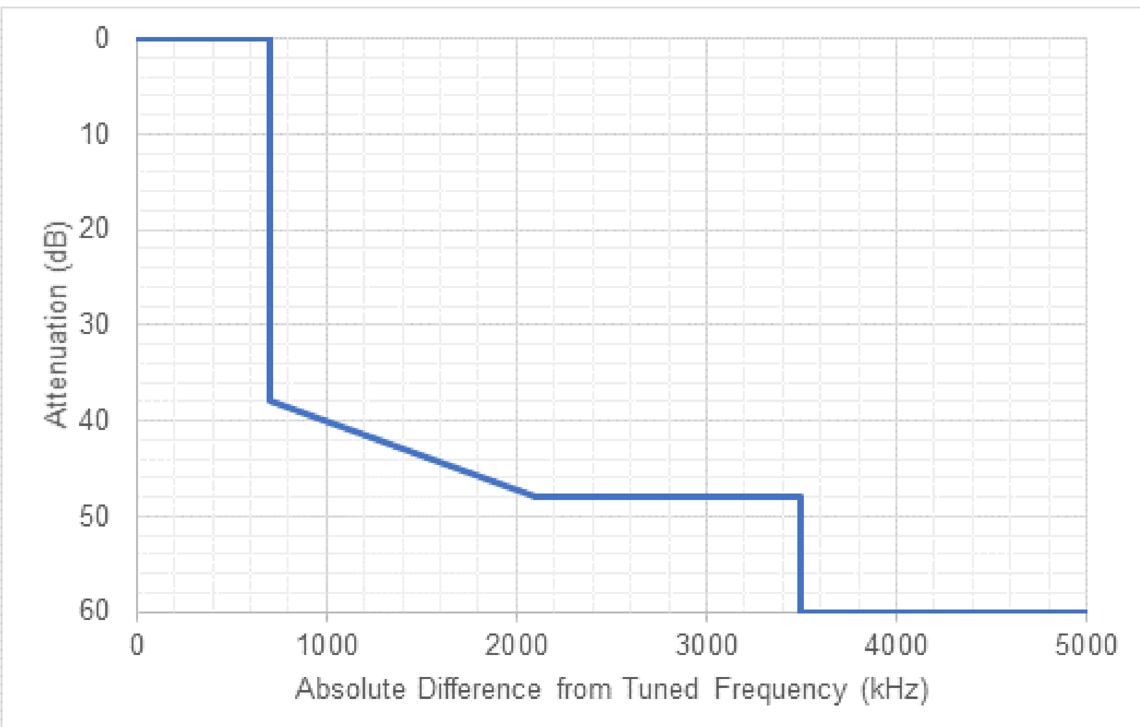


Figure 4-1. Example of Transmitter Mask, Expressed as Attenuation Values

Figure 4-2 presents an example of a receiver mask.

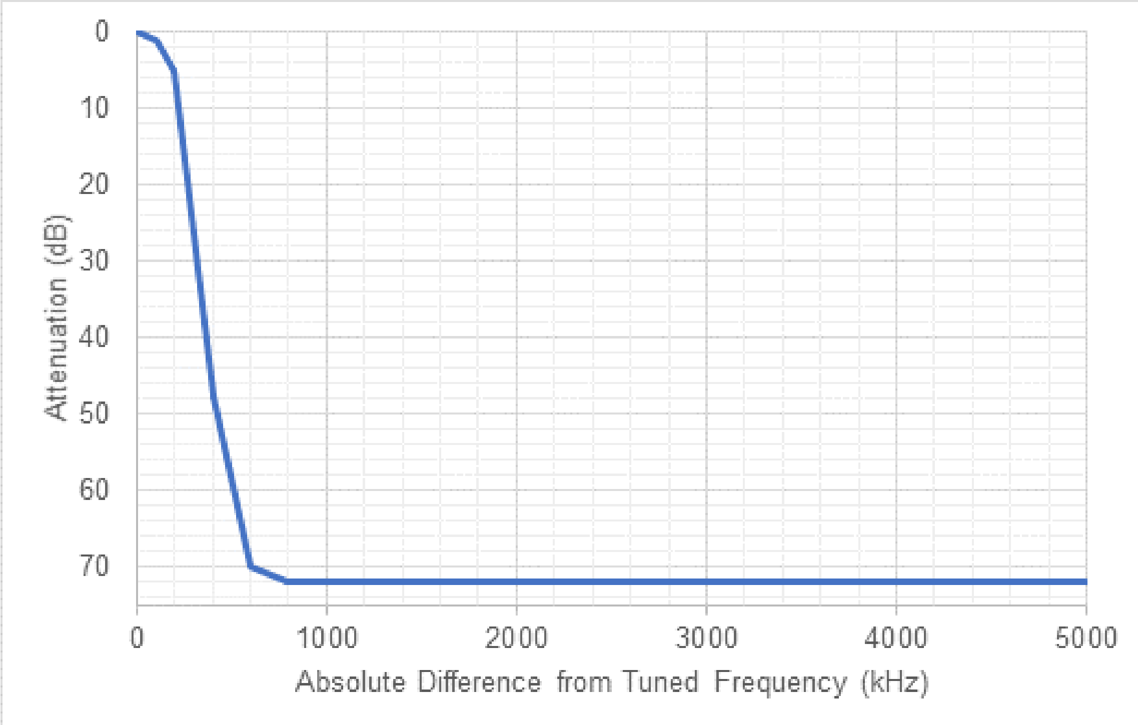


Figure 4-2. Example of Receiver Mask, Expressed as Attenuation Values

Figure 4-3 shows an FDR curve that was calculated using (4-3) and the two masks depicted in Figures 4-1 and 4-2.

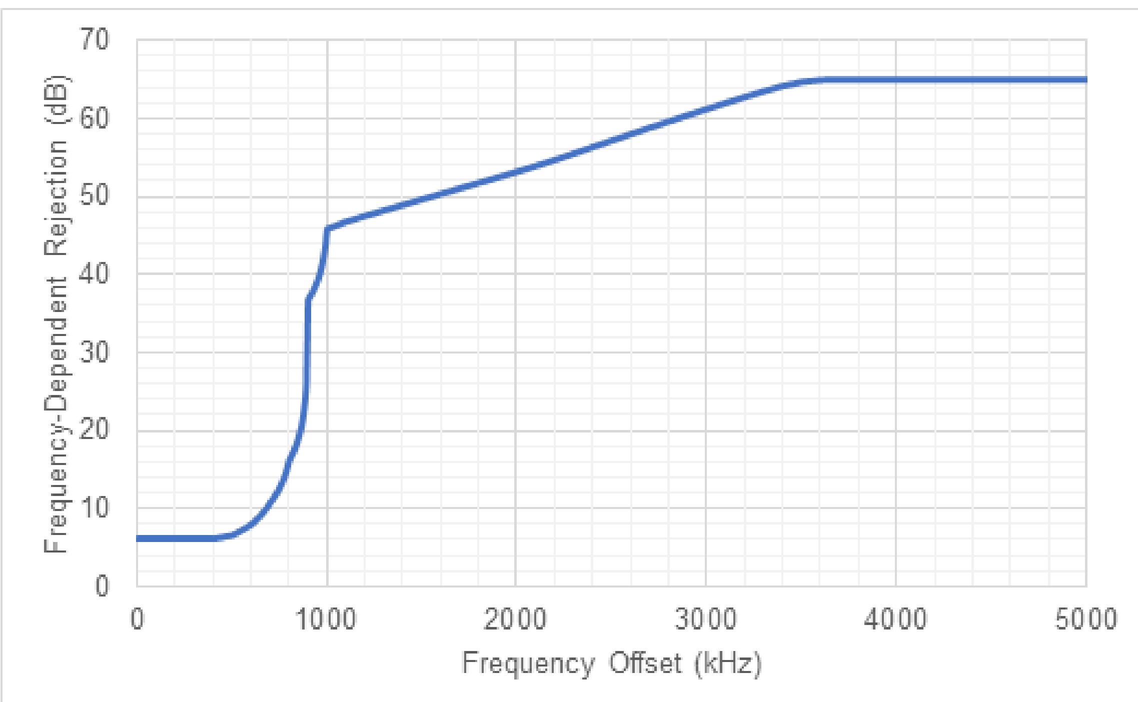


Figure 4-3. Example of Calculated FDR Curve

The value of Δf at which an FDR curve, calculated by evaluating (4-3), is guaranteed to level off at its final maximum value is $\Delta f_{max} = (B_{ft}/2) + (B_{fr}/2)$, where $B_{ft}/2$ and $B_{fr}/2$ are the f values at which the transmitter and receiver masks, respectively, reach their maximum attenuation values. Further increases in Δf can have no effect on calculated FDR, since no overlap remains between the parts of the two masks with submaximal attenuations. In the example of Figures 4-1 through 4-3, B_{ft} = 7000 and B_{fr} = 1600, and so Δf_{max} = 4300 kHz.

5 The Antenna Model

The MAFS-calculation procedures discussed in Section 3.5 depend on an automated antenna model, described in this section, to compute worst-case off-axis antenna-gain attenuations in a wide variety of situations for use in the expressions of Section 3. (Section 5.4 explains the meaning of “worst case” in this context.)

Note: Installation losses (e.g., waveguide, cable, and/or connector losses) that attenuate signals traveling between a radio and its own antenna are not considered explicitly in FAFu. Instead, any such losses are to be subtracted by the user from antenna gain before specifying a gain value for use by the program. Consequently, the term “antenna gain” in this report is generally intended to mean “antenna gain minus installation losses, if any.”

5.1 Input Parameters

Before assigning a frequency to a CNPC link, FAFu needs to know the polarization and maximum gain of each of the link’s ground-based and airborne antennas. For each ground-based antenna, it also needs to know whether the antenna is directional. (Airborne antennas are assumed always to be omnidirectional, at least in the initial version of FAFu.) If a ground antenna is directional, FAFu also must know the direction in which the antenna points, or, if the antenna is steerable, the azimuthal sector within which it can be steered.

Each directional ground antenna must also have a specified azimuthal antenna-pattern mask, discussed below. (Elevation-plane and three-dimensional antenna patterns are not considered in the initial version of FAFu, since an excessively complex model would be needed to take them into account.)

FAFu allows, but does not require, any given UAS to have different antenna characteristics for its uplink and downlink. The relevant parameters are listed below.

5.1.1 Uplink Parameters

- Uplink signal polarization (character field: H = horizontal, V = vertical, C = circular, R = right-hand circular, L = left-hand circular, O = other or unspecified). This is the polarization of the ground transmitting antenna and the airborne receiving antenna.
- Ground transmitting antenna’s maximum gain in dBi.
- Ground transmitting antenna’s pattern-mask number, allowing FAFu to look up a previously provided mask in its database of equipment characteristics. The number 0 (zero) is reserved for an idealized omnidirectional antenna whose gain is assumed to be constant in all directions.
- Ground transmitting antenna’s steerability indicator (character field: F = fixed; L = steerable within limits; A = steerable in all directions).
- Ground transmitting antenna’s azimuthal steerability limits, in degrees measured clockwise (CW) from true north. These are the counterclockwise (CCW) and CW limits of the azimuthal range of antenna boresight (the direction of the antenna’s maximum gain). Each limit is expressed as an angle at least 0 but less than 360 degrees CW from true north. If the antenna is omnidirectional, the term “boresight” is meaningless and the program automatically sets both limits to zero. Otherwise, if the

ground antenna is fixed, then the boresight azimuth angle never changes and the two limits must be identical, so the program automatically sets the CW limit equal to the user-specified CCW limit. If the ground antenna is steerable within limits, the CCW and CW limits are user-defined and must not be identical. If the ground antenna is steerable in all directions, then the boresight can point in any azimuthal direction, and the CCW and CW limits are undefined.

- Airborne receiving antenna's gain in dBi.

5.1.2 Downlink Parameters

- Downlink signal polarization (same choice of values as shown above for uplink polarization). This is the polarization of the airborne transmitting antenna and the ground receiving antenna.
- Airborne transmitting antenna's gain in dBi.
- Ground receiving antenna's maximum gain in dBi.
- Ground receiving antenna's pattern mask number, where 0 means "omnidirectional."
- Ground receiving antenna's steerability indicator (F, L, or A).
- Ground receiving antenna's CCW and CW steerability limits, in degrees measured clockwise from true north. (The explanation provided above for the ground transmitting antenna's steerability limits applies here as well.)

5.2 Antenna Masks

An antenna mask in FAFu is a curve that encloses an azimuthal radiation pattern and varies monotonically from boresight (the azimuthal direction of maximum gain, also called the "axis" of the antenna pattern) to the direction that is 180° opposite boresight. The curve does not show actual gain values but instead shows off-axis attenuation as a function of angular difference from boresight. Figure 5-1 depicts an example of a mask (in red) enclosing a measured or predicted radiation pattern (in black). Note the nulls in the radiation pattern. The reason for using masks instead of actual radiation patterns is that the exact positions of nulls are notoriously unpredictable and thus, to avoid excessively optimistic interference predictions, are generally not considered when assigning frequencies.

FAFu antenna masks are always symmetrical around boresight. The user enters only the half of the mask that is clockwise from boresight, and the program then will assume the CCW half is the mirror image of the CW half. The half-mask must contain at least two points (at 0 and 180 degrees), but not more than 100 points in all. The attenuation values must begin with 0.0 dB for an off-axis angle of 0 degrees (boresight), increase monotonically as off-axis angle increases, and reach a maximum when the off-axis angle reaches 180 degrees. The points do *not* need to be evenly spaced, either in angle or in attenuation. Table 5-1 shows an example of a manual-entry window for the CW half-mask. (Note: The hypothetical mask specified in Table 5-1 is different from the one depicted in Figure 5-1.)

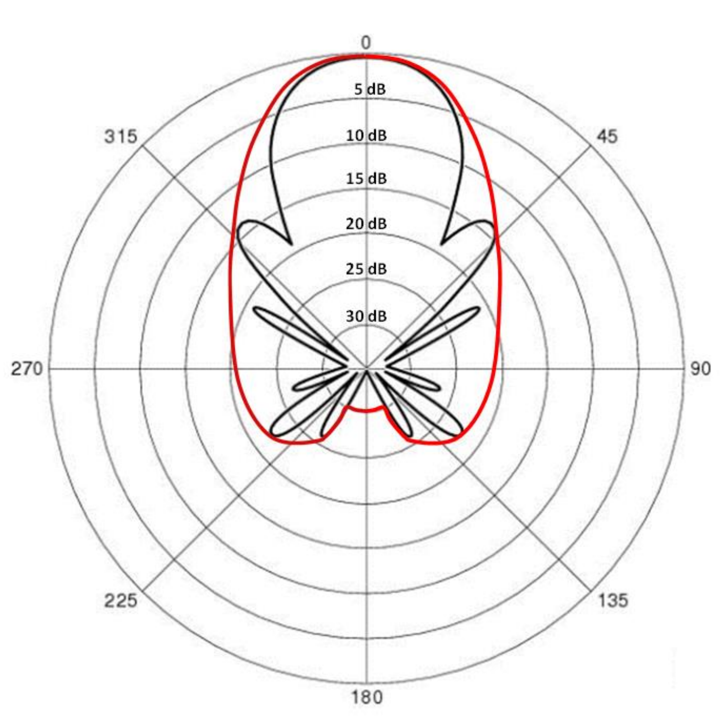


Figure 5-1. An Azimuthal Antenna Pattern and Its Mask

Table 5-1. Example of User-Defined Antenna Half-Mask

Off-Axis Angle (Degrees from Boresight)	Off-Axis Attenuation (dB)
0.0	0.0
3.5	0.5
6.3	3.1
10.0	10.5
20.0	28.7
180.0	41.0

After the mask has been defined, FAFu assigns it a previously unused antenna-mask number and stores it in the ETC database. Each antenna-mask record contains the following fields:

- Antenna mask number.
- The total number (2–100) of points in the user-specified half-mask.
- Coordinates (off-axis angle and attenuation) of first point in the half-mask. (Both coordinates must monotonically increase from one point to the next.)

  ...

- Coordinates of last point in the half-mask.

During subsequent calculations, discussed in Section 5.4, the program linearly interpolates between adjacent mask points whenever called upon to calculate off-axis attenuation in a direction of interest.

5.3 Displaying Antenna Icons

During FAFu operation, each directional ground antenna can be displayed on the FAFu manager's map screen, at the option of the manager, as a wedge (or a circle if the antenna is omnidirectional) as illustrated below using solid lines. The angle of the wedge should be equal to the half-power beamwidth (the width of its azimuthal pattern corresponding to a mask attenuation of 3 dB). In the case of a steerable antenna, the icon needs to indicate possible antenna orientation by extending the wedge using dashed lines. The apex of the wedge (or the center of the circle) will be the location of the GS as shown on FAFu's map display.

Figure 5-2 depicts an icon for a steerable antenna with a 3-dB beamwidth of 68°, a CCW scan limit of 303°, and a CW scan limit of 57°.

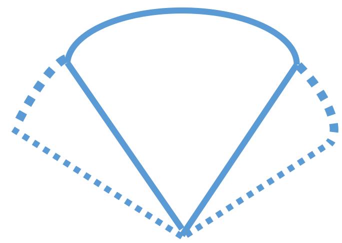


Figure 5-2. Screen Icon for Steerable Antenna

5.4 Antenna Gain Calculations

When performing MAFS calculations in preparation for identifying compatible frequencies, FAFu repeatedly uses the previously specified antenna parameters to compute off-axis gain attenuation (if any) in the direction of propagation toward or away from the antennas of other GSs and UA that are transmitting or receiving desired or undesired signals. The procedure used to compute the attenuation in any particular case depends, among other things, on whether the antenna under consideration is omnidirectional, fixed, or steerable, and on whether the signal is desired or undesired.

Figure 5-3 depicts the procedure for computing off-axis ground-antenna gain attenuation in the direction of propagation to or from the SV of an aircraft. Every SV has either a circular or a polygonal horizontal cross section, and can be treated either as "desired" or "undesired" in particular calculations. When a desired signal is traveling to or from a given SV, that SV is treated as the "desired" SV for the purposes of that calculation. Conversely, an "undesired" SV is one from which or to which the undesired signal is propagating.

The purpose of FAFu's antenna-gain calculation function is to compute the worst-case value of off-axis gain attenuation to which the SV under consideration is exposed. The worst case is the one that will tend to minimize the desired-to-undesired power ratio at the input to the victim receiver. For a desired SV, the worst case is the *maximum* off-axis attenuation (G_{tda} or G_{rda}), which occurs at a "critical point" where the off-axis angle α_d is largest. But for an undesired SV, the worst case is the *minimum* off-axis attenuation (G_{tua} or G_{rua}) that exists at a critical point where off-axis angle α_u is *smallest*.

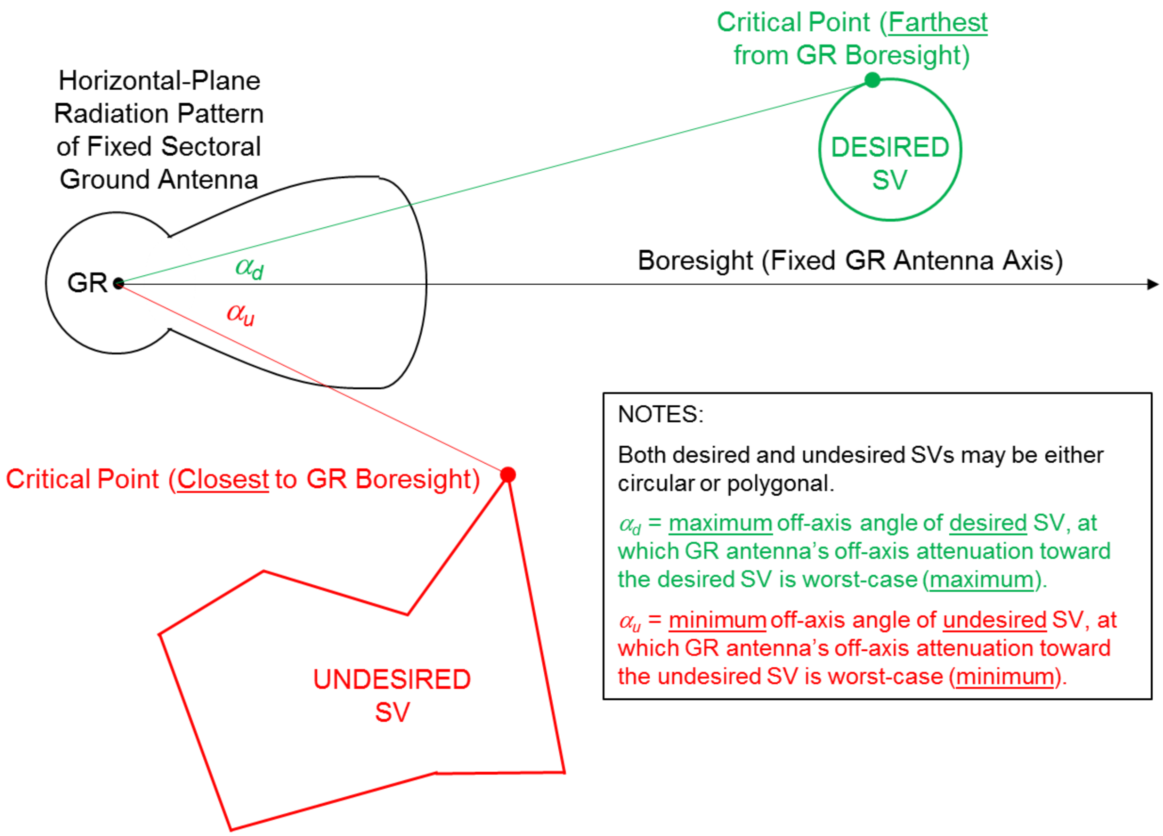


Figure 5-3. Calculation of Fixed-Axis Ground-Antenna Gains

When multiple undesired-signal propagation paths are considered for a given source/victim equipment pair, as discussed in Section 3.5.1, a separate value of α_u must be calculated for each propagation path, and gain values must be calculated for all of those paths, not just the one at the critical point. For *desired* signals, however, only one value of α_d needs to be considered, as indicated in Figure 5-3.

Figure 5-4 depicts the calculation procedure for a steerable-beam ground antenna. Here, when calculations are made for the *desired* SV, the GR antenna is assumed to track the aircraft by steering its boresight directly toward the UA whenever the aircraft remains between the CCW and CW limits (if any) of the GR's steerability sector. Thus, if the desired SV lies entirely within the steerability sector, α_d is zero and so is the off-axis attenuation. However, if any part of the desired SV lies outside the steerability sector, then α_d and the resultant worst-case (maximum) off-axis attenuation are computed from the location of the desired SV's critical point, as illustrated in the figure.

When making calculations for the *undesired* SV, the GR antenna is *not* necessarily assumed always to be tracking the UA in the desired SV. Instead, as shown in Figure 5-4, the program conservatively assumes the steerable beam may be pointing anywhere between the CCW and CW steerability limits. It computes α_u and resultant off-axis attenuation at the undesired SV's critical point—i.e., the point in the SV having the smallest angular distance from the nearer of the two GR-antenna scan limits. This could sometimes lead to unduly conservative predictions. For that reason, FAFu users should be encouraged to define steerability limits as narrowly as possible while still enclosing the full extent of the associated SV.

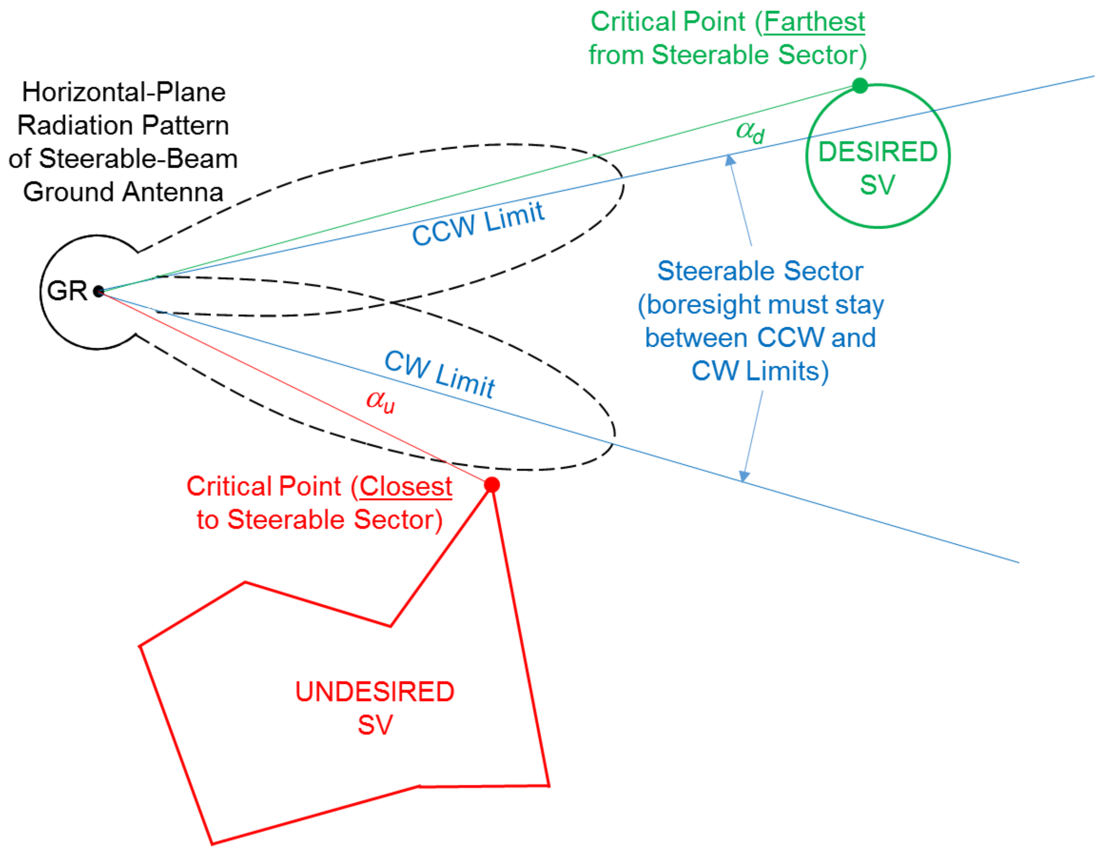


Figure 5-4. Calculation of Steerable-Beam Ground Antenna Gains

5.5 Cross-Polarization

The cross-polarization discrimination factor X discussed in Section 3.5 depends on the antenna polarizations of the *undesired* transmitter and the receiver. Those polarizations are the same as the signal polarizations of the respective links to which they belong. If the polarizations are orthogonal—i.e., if one is H and the other is V, or if one is R and the other is L—then FAFu assumes X = 6 dB. If one polarization is linear and the other is circular—i.e., if one is H or V while the other is C, R, or L—then X = 2 dB. For all other polarization combinations, X = 0 dB. Much higher cross-polarization values would be feasible for the orthogonal cases if both antennas were on stable platforms. The conservative values used here are based on the fact that a rolling, pitching, or yawing UA will change its antenna's orientation enough to prevent the rejection from being as complete as it might be if the antenna were mounted on a fixed surface. They also allow for variances between the intended and actual polarization characteristics of installed antennas, especially airborne ones.

6 The Propagation Model

The purpose of the FAFu propagation model is to calculate L_{au} (T_{pc}), the attenuation value that is predicted to equal or exceed, T_{pc} percent of the time, the additional path loss (in excess of free-space loss) actually undergone by the undesired signal as a result of terrain and atmospheric effects as it travels from the undesired transmitter T_u toward the potential victim receiver R. (For the reasons explained in Section 3.5, FAFu predicts additional loss only for *undesired* signals, not for desired signals.) Propagation-loss calculations are computationally intensive and are likely to consume much of FAFu's running time. The design of FAFu's propagation module will require careful tradeoffs between accuracy and speed.

The propagation mechanisms with the most significant impacts on undesired-signal path loss in CNPC links between 1040 and 5091 MHz are:

1. Free-space loss, already described in equation (3-5)
2. Terrain loss (blocking and diffraction)
3. Atmospheric refraction (including ducting), which occasionally carries undesired signals far beyond the nominal 4/3-earth radio horizon.

Less important mechanisms include:

4. Atmospheric gaseous absorption, which is quite small at these frequencies
5. Precipitation loss (which is small at these frequencies and too infrequent to provide significant protection against RFI)
6. Tropospheric scattering (which can carry undesired signals beyond the radio horizon but attenuates them much more than refractive effects do).

We have evaluated two major propagation models for their potential in modeling these effects for FAFu: the Terrain-Integrated Rough-Earth Model (TIREM) and the ITU-R P.2001 model [6]. Both models cover all the mechanisms listed above.

TIREM was developed in the 1960s and was upgraded repeatedly through at least the mid-1990s, but the latest publicly available comprehensive documentation appears to be [7], which was published in 1994. Proprietary TIREM software is available from a private source. It has been incorporated into numerous U.S. Government and commercial spectrum-management and communications-planning tools over the years. As stated in [7], "TIREM is designed to calculate basic median propagation loss … over irregular terrain for frequencies between 1 and 20,000 MHz."

The P.2001 model was developed much more recently by ITU-R. No automated version is generally available. It covers the frequency range from 30 to 50,000 MHz. It considers "the small-probability tails of both fading and enhancement distributions" of propagation path losses. Unlike TIREM, it can provide cumulative distributions of path losses as a function of T_{pc}. For that reason, together with the fact that full details of the current version of the P.2001 model are publicly available, we recommend it for incorporation into FAFu, provided that ongoing validation studies continue to show favorable results. One such study [8] found P.2001's diffraction submodel (the delta-Bullington model discussed below) to be well suited for interference and frequency-coordination analyses.

6.1 Terrain Loss

Terrain loss occurs mainly because obstacles such as hills, mountains, and clutter (i.e., buildings and trees) can block the direct path between a transmitter and a receiver, preventing the existence of a RLOS. Calculating the magnitude of the loss is made much more difficult by the fact that electromagnetic diffraction allows some of the energy in the blocked signal to propagate beyond the intervening obstacle and reach the receiver, although weakened (often very substantially) in comparison with the signal that would have been received if a RLOS had existed. However, such calculations are important because quantifying the diffraction loss allows FAFu to screen out some potential interference cases that might otherwise prevent it from finding a frequency for a particular CNPC link.

In some cases, of course, considering terrain enables FAFu to identify interference cases that would otherwise have been overlooked. For example, an undesired CNPC ground transmitter or potential victim receiver may be on a mountaintop that is visible from some point in the SV of a different UAS too far away to have had a direct RLOS to a GR at the base of the mountain.

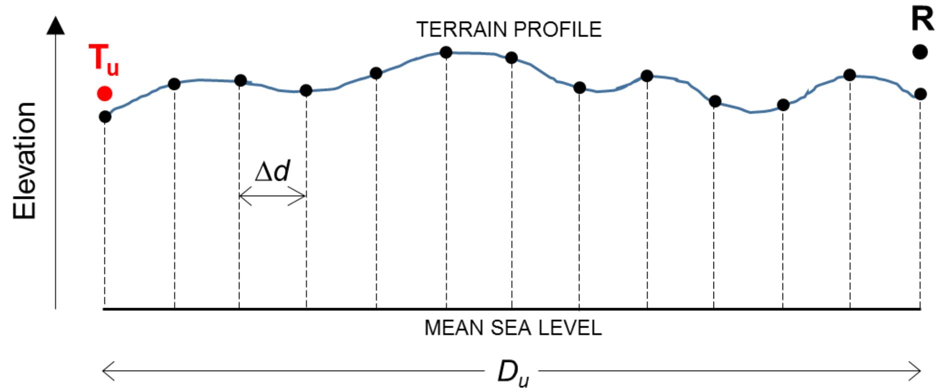
FAFu's terrain-loss algorithms use a topographic database that stores ground elevations in feet above mean sea level (AMSL), so the maximum (worst-case) GR and AR heights provided to those algorithms must also be AMSL. The height AMSL of a GR is the sum of the GR's antenna height above ground level (AGL) and its GS's site elevation AMSL. The AR height equals the SV ceiling altitude of its UA, which the user defines as a constant value that can be either AGL or AMSL. If the SV ceiling altitude has been defined AGL, FAFu adds it to the *highest* terrain elevation recorded in the topographic database for the area beneath the SV to obtain the ceiling altitude AMSL. (Since the true altitude AMSL of an SV ceiling having a constant altitude AGL would actually vary with latitude and longitude just as much as the underlying terrain elevation, using the highest terrain elevation to compute the AMSL value is a conservative assumption, but the need for computational tractability and speed necessitates it.)

Predicting terrain loss along a given propagation path between an undesired transmitter and a potential victim receiver requires execution of the following steps:

1. Defining the terrain profile (including clutter data, if available) along the path
2. Identifying the terrain obstacle(s) that block or most closely approach the direct RLOS between the undesired transmitter and the receiver
3. Calculating diffraction loss along the path as a function of signal frequency and the height and distance of the obstacle(s).

6.1.1 Defining Terrain Profiles

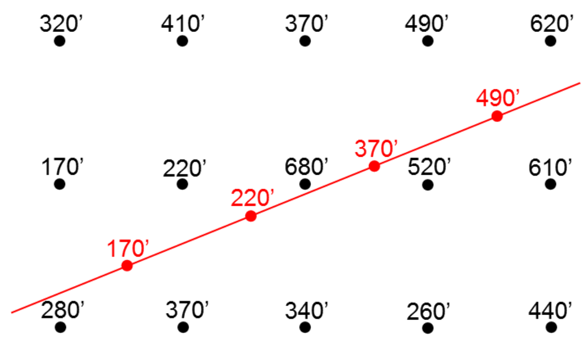
FAFu identifies sample points at equal distance intervals Δd along each great-circle path between undesired transmitter T_u and potential victim receiver R, as shown in Figure 6-1. The figure also indicates the antenna height of each radio (or its SV ceiling height, if applicable) above terrain.



Sample points are spaced at equal intervals along great-circle path between undesired transmitter and potential victim receiver

Figure 6-1. Sampling Terrain Elevations Along a Radial

Few if any of the sample points are likely to coincide with the latitude/longitude gridpoints in which FAFu's topographic database stores terrain-elevation data, so interpolation is necessary to estimate terrain elevations at the sample points. Figure 6-2 illustrates the process. For conservatism, since FAFu is concerned here only with *undesired* signal paths, the program assumes that each sample point is at the same elevation as the *lowest* of the four neighboring database gridpoints. This assumption is intended to minimize the chance that FAFu will mistakenly perceive a terrain blockage when in fact an unobstructed RLOS exists between the undesired transmitter and the victim receiver.



Plan view showing part of great-circle path between undesired transmitter and potential victim receiver, with terrain elevation (AMSL) at nearby gridpoints. Each sample point along path is assumed to have the lowest elevation of any of the four closest gridpoints.

Figure 6-2. Conservative Method of Interpolating Between Terrain Data Points

6.1.2 Identifying Terrain Obstacles

After defining the terrain profile along a path, FAFu computes the elevation angle of each sample point along the profile as seen from the undesired transmitting antenna. The highest such angle defines the transmitter's horizon in the direction of propagation. FAFu repeats the process for the receiver. Depending on circumstances, a single obstruction may define the horizons of both the undesired transmitter and the receiver, as shown in Figure 6-3, or each may have its own horizon-defining obstruction, as in Figure 6-4.

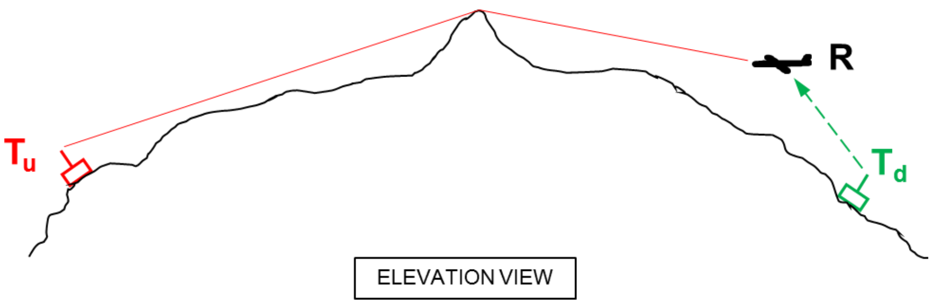


Figure 6-3. Path with Single Predominant Obstruction

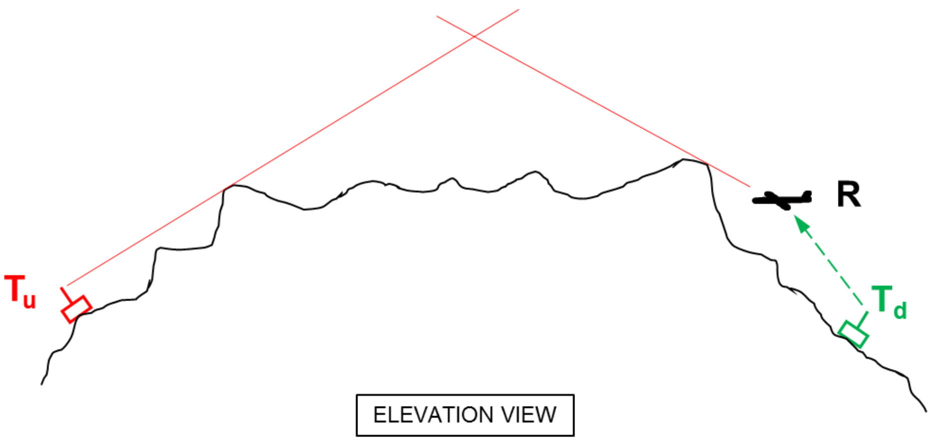


Figure 6-4. Path with Multiple Obstructions

The apparent elevation angle θ of any obstruction, as seen from either T_u or R, is affected by the fact that the earth's curvature makes an object D nmi away seem lower than its actual height by an amount equal to $(D/1.0652)^2/K = 0.8813D^2/K$, where K is the effective-earth's-radius ratio. (See the discussion in Section 3.4.) Consequently, FAFu computes the elevation angle as

$$\theta = \tan^{-1}\left(\frac{H_O - H_A - \left(0.8813D^2/K\right)}{6076.115D}\right), \tag{6-1}$$

where H_O and H_A are the respective heights (in feet AMSL) of the obstruction and the radio antenna at either end of the link. If, as usual, K is assumed to be 4/3, (6-1) becomes

$$\theta = \tan^{-1}\left(\frac{H_O - H_A - 0.661D^2}{6076.115D}\right). \tag{6-2}$$

6.1.3 Calculating Diffraction Loss

Several computational models exist for calculating diffraction loss over a rough earth. These include the single-knife-edge, the Bullington double-knife-edge, and the delta-Bullington models discussed below.

Single Knife Edge: The simplest case, illustrated in Figure 6-5, involves a path with a single dominant obstruction that is narrow enough to be modeled as a "knife edge" [9, p. 16ff.]. The three distances shown in the figure, D_{u1}, D_{u2}, and H, are all expressed in the same units. The obstruction is D_{u1} units from the undesired transmitter and D_{u2} distance units from the receiver. The peak of the obstruction is H units above the direct path between the transmitter and receiver. (If the peak happens to lie *below* the direct path, so that T_u and R are mutually visible, then H is negative.)

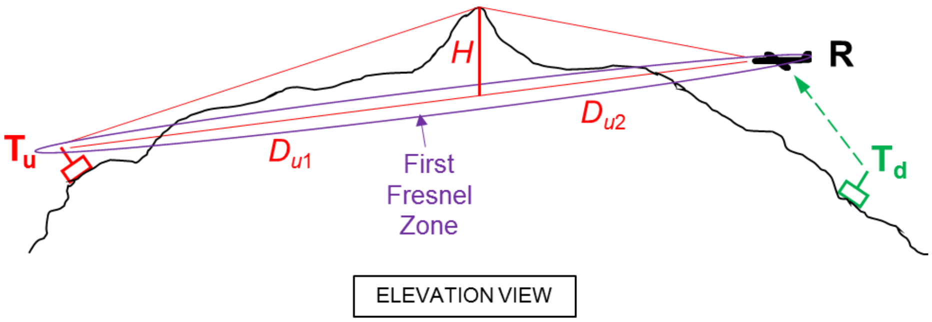


Figure 6-5. Single-Knife-Edge Diffraction Model

The effect of diffraction on received signal strength depends heavily on whether the peak of the obstruction is above, within, or below the first Fresnel zone. That zone, depicted in Figure 6-7, is an ellipsoid of revolution whose axis coincides with the direct path and whose foci are the locations of the antennas of T_u and R. The sum of the distances from each point on the ellipsoid to T_u and R is equal to half of signal wavelength λ, expressed in the same units as D_{u1}, D_{u2}, and H. The radius of the first Fresnel zone, also in the same units, at the point on the path where the knife-edge obstructs it is

$$F_1 = \sqrt{\frac{\lambda D_{u1} D_{u2}}{D_{u1} + D_{u2}}} \,. \tag{6-3}$$

Suppose, for example, that D_{u1} = 15 nmi (27,780 meters (m)), D_{u2} is 10 nmi (18,520 m), and the undesired signal frequency is 5060 MHz (so that λ = 0.059249 m). Then the first Fresnel zone has a radius of 25.7 m at the point on the undesired-signal path where the obstruction is located.

If the obstruction lies entirely below the first Fresnel zone, its influence on path loss is relatively small, but the farther it penetrates into or beyond that zone the more substantial its impact becomes. To facilitate loss calculations, [9] defines a dimensionless parameter

$$\nu = \frac{\sqrt{2}H}{F_1} = H\sqrt{\frac{2}{\lambda}\left(\frac{1}{D_{u1}} + \frac{1}{D_{u2}}\right)} \,. \tag{6-4}$$

When $\nu \leq -0.78$, diffraction loss L_d always remains within the range from –1.3 to 1.3 dB [9, p. 19] and thus may reasonably be approximated as 0 dB. When $\nu > -0.78$, the diffraction loss is always positive and can be approximated as

$$L_d \approx 6.9 + 20\log\left(\sqrt{(\nu - 0.1)^2 + 1} + \nu - 0.1\right) \text{ dB.} \tag{6-5}$$

Returning to the foregoing example, if the peak of the obstruction lies 15.4 m (0.6 times the Fresnel-zone radius) *below* the direct path, then H = –15.4 m, ν = –0.85, and L_d = 0 dB (i.e., no diffraction loss). If the peak just touches the direct path, then $H = \nu = 0$ and L_d = 6 dB (i.e., 6 dB of diffraction loss). If the peak touches the top of the first Fresnel zone, then H = 25.7 m, ν = 1.414, and L_d rises to 16 dB. Tripling H to 77.1 m would raise ν to 4.24, and L_d to 25 dB.

Double Knife Edge: It often happens that no single obstruction is visible to both the transmitter and the receiver. Figure 6-6 depicts such a situation, in which separate obstructions define the horizons of the transmitter and receiver. The oldest, simplest, and fastest way to estimate diffraction loss in such cases is Bullington's "double-knife-edge" model [10], [11, pp. 77–78].

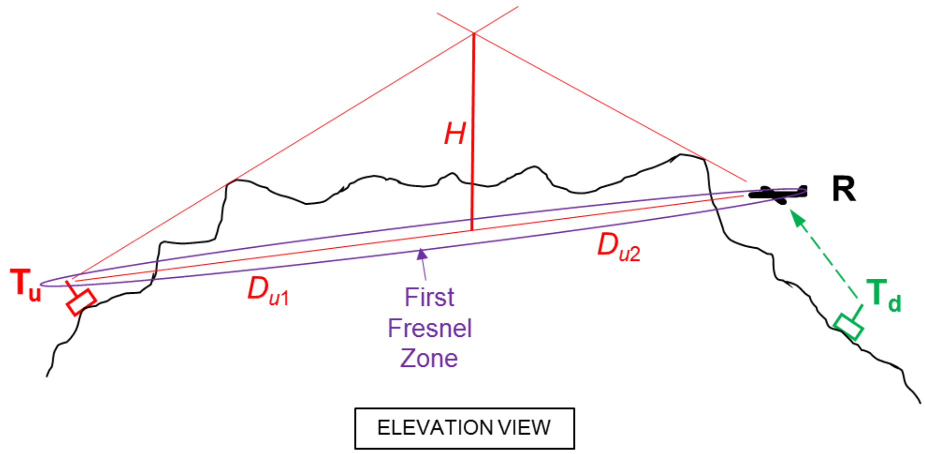


Figure 6-6. Bullington's Double-Knife-Edge Diffraction Model

The Bullington double-knife-edge method is as follows:

1. Find the point where the obstruction-grazing rays from T_u and R intersect.
2. Treat that point as if it were the peak of a single knife-edge obstruction in determining the values of D_{u1}, D_{u2}, and H.
3. Enter those values into equation (6-4) and then use (6-5) to estimate diffraction loss.

Delta-Bullington: This model [6, sec. 4.5] was developed to improve the accuracy of the traditional Bullington model in computing diffraction loss. It has been incorporated into the P.2001 model. The diffraction loss is calculated by combining Bullington's diffraction method (introduced above) and a separate spherical-earth diffraction method. The Delta-Bullington diffraction method is as follows:

1. Use the Bullington algorithm, described above, with the actual path profile and actual antenna heights to compute the actual-profile Bullington diffraction loss, L_{dba}.
2. Use the same Bullington algorithm again, but with a zero-height smooth path profile and modified effective antenna heights, to compute the smooth-profile Bullington diffraction loss, L_{dbs}.
3. Use the algorithm in [6, A.2], with the same modified effective antenna heights as in step 2, to compute the spherical-earth diffraction loss, L_{dsph}.
4. Calculate the diffraction loss by combining the three losses from steps 1–3. The final output of this model is $L_d = L_{dba} + \max(L_{dsph} - L_{dbs}, 0)$.

This procedure enables a smooth transition between free-space and obstructed conditions. For a perfectly smooth path, the final diffraction loss would be the output of the spherical-earth model. The predicted loss is sensitive to the terrain resolution.

6.2 Atmospheric Effects

The atmosphere is another key determinant of propagation loss. Different combinations of air temperature, air pressure, gas density and water in the atmosphere affect radio propagation in many ways. Certain combinations can cause radio signals to be detected far beyond the radio horizon. The major weather-associated mechanisms that can cause signals to travel over such long distances are:

- Refractive effects
- Scattering from rain and eddies in the air

Conversely, certain combinations of factors can cause notable attenuation, so the radio signal may be unexpectedly weakened before it reaches the receiver.

6.2.1 Anomalous Propagation (Ducting and Layer Refraction)

Since pressure and temperature generally decline as altitude increases, the refractive index of the atmosphere usually falls with the increasing height. Radio waves are generally bent downward because of the change of refractive index from a denser to a rarer medium. The relation between altitude and refractive index in a simplified situation involving three atmospheric layers, each having its own uniform refractive index, is shown in Figure 6-7. This downward bending can compensate more or less for the curvature of the earth, so the radio waves can potentially propagate beyond the geometric horizon.

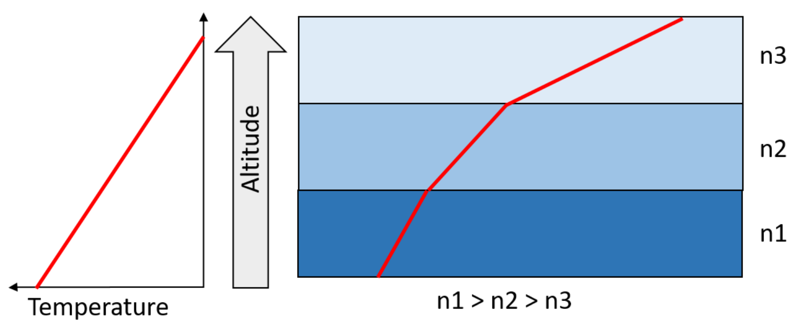


Figure 6-7. Refractive-Index Variation with Height

The refractive index n of air is very close to 1.0003. Normally, the more convenient parameter N is used to represent refractivity: $N = (n - 1) \times 10^6$. Radio wave propagation depends more on the gradient of refractivity versus height (dN/dh) than on the absolute value of refractivity at any point. Depending on existing conditions (variations in pressure, temperature and humidity) in the troposphere, radio waves can experience various types of refraction: sub-refraction, standard refraction, super-refraction and trapping/ducting. Figure 6-8 illustrates these types of refraction. If $dN/dh > 0$ N-units/km, a sub-refractive condition exists and radio waves will bend upwards, away from the surface of the earth. If $-79 < dN/dh < 0$ N-units/km, the curvature of the radio wave will be less than the earth's curvature. In a standard atmosphere, normal propagation is found with refractivity gradient about –40 N-units/km (which corresponds to the well-known "4/3 earth"). When $-157 < dN/dh < -79$ N-units/km, a super-refractive condition occurs in the troposphere and the radio wave will refract downwards at a rate greater than standard but less than the curvature of the earth. Finally, if the gradient of refractivity falls below –157 N-units/km, radio waves will bend towards the earth's surface with a curvature greater than that of the earth, which means effective earth radius becomes infinite. (Normally, the effective earth radius is 8500 km, whereas the actual radius of the earth is 6371 km, so the ratio—i.e., the "*K* factor"—is about 4/3.) This phenomenon is called "trapping," and is particularly important in the context of evaporation ducts.

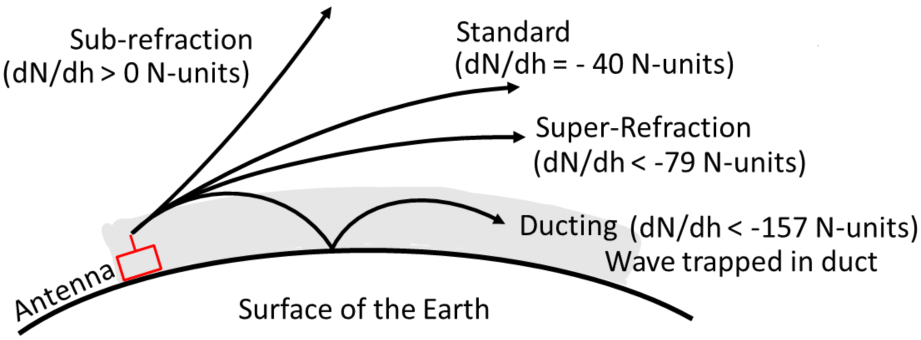


Figure 6-8. Effects of Changes in Refractivity Gradient

As mentioned before, the warmest air is found near the surface of the earth under normal atmospheric conditions, and the air becomes cooler with increasing altitude. However, abnormal atmospheric conditions can lead to anomalous propagation. An unusual situation happens when a warm air layer forms above a cool air layer, which leads to a phenomenon called temperature inversion. Figure 6-9 compares usual and unusual atmospheric patterns. The altitude of the inversion layer for non-ducting is typically found between 300 and 3000 feet and for ducting between 1600 and 10,000 feet, and the event durations are typically from several hours up to several days. Temperature inversion can happen when the air near the ground rapidly loses its heat on a clear night. In this situation, the ground becomes cooler than the air above, which retains the heat that ground was holding during the day. This phenomenon can also occur over large lake areas because upwelling of cold water can decrease surface air temperature and the cold air mass stays under warmer ones.

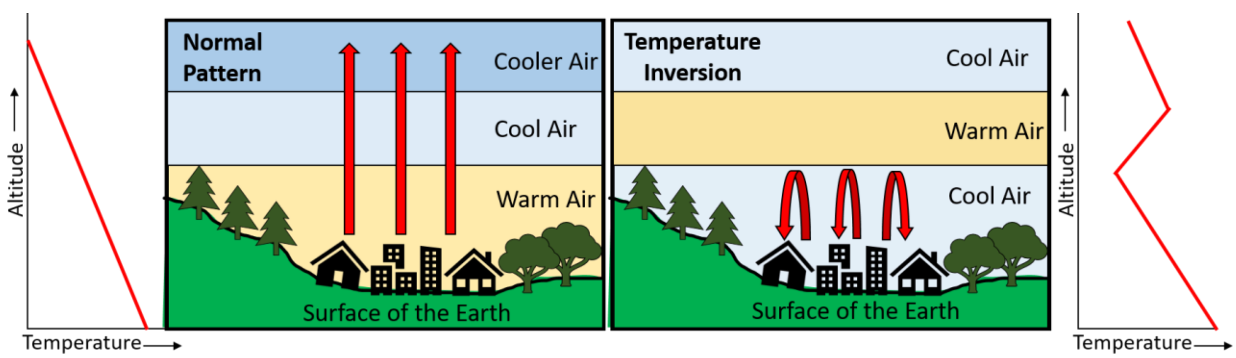


Figure 6-9. Normal Atmospheric Pattern versus Temperature Inversion

Temperature inversion causes a duct of cool air to be sandwiched between the surface of the earth and a layer of warm air, or between two layers of warm air. If radio waves enter this temperature-inversion layer/duct at a very low angle of incidence, they may be trapped and bounce back and forth between the upper and lower boundaries of the duct. When a radio wave enters the warm air above the duct, the sudden change in density causes the wave to be refracted back toward the surface of the earth. On the other side, when the radio wave hits the surface of the earth or a warm layer below the duct, it is again reflected or refracted upward. This is known as the duct effect. In this situation, radio waves may propagate hundreds of miles, far beyond normal RLOS distances. Therefore, when a temperature inversion forms and gives rise to the duct effect, it is possible that the victim receiver (R) might suffer interference from undesired transmitter T_u, as depicted in Figure 6-10. FAFu applies the P.2001 model [6, p. 36ff.] to calculate the loss due to anomalous propagation, which includes ducting and layer reflection/refraction. Transmission loss associated with anomalous propagation is a function of operational frequency, path profile, radio-climatic zone, and refractivity gradient. Radio-climatic zones are classified into coastal land (code A1), inland (A2), and sea (B), and are defined in the ITU Digital World Map (IDWM).

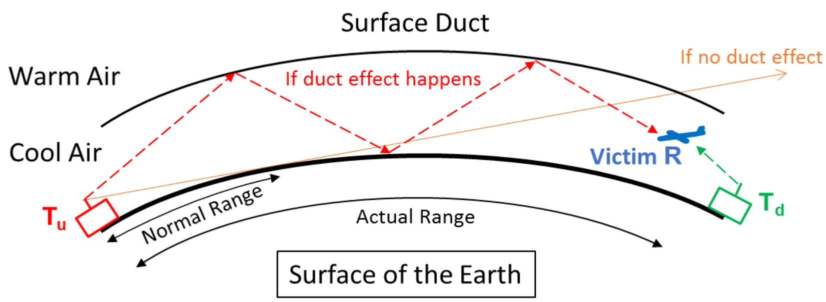


Figure 6-10. Ducting Effect Caused by Temperature Inversion

6.2.2 Precipitation Attenuation

Rain is the form of precipitation with the largest effect on radio waves. Attenuation due to rain is generally proportional to the frequency and the wavelength. It becomes more severe at wavelengths approaching the water-droplet size. As the wavelength becomes shorter with increases in frequency, rain attenuation increases.

Attenuation may be caused by absorption, in which the raindrop, acting as a poor dielectric, absorbs power from the radio wave and dissipates the power by heat loss, or by scattering. Raindrops cause greater attenuation by scattering than by absorption at frequencies above 3 gigahertz (GHz). Rain scatter can also cause microwave signals to propagate beyond RLOS.

Rain attenuation also increases with rain rate [12], which can range from very light (less than 0.25 mm/hour) to extreme (over 50 mm/hour). Total rain attenuation can be evaluated by integrating the specific attenuation along the path. The model uses the location of the midpoint of the propagation path to ascertain rain climatic parameters.

Since rain attenuation is fairly small below 6 GHz, FAFu will not incorporate this submodel for use in undesired signal-strength calculations, at least not in the short term. (However, users should take the rain fading of the *desired* signal into account in the link budgets they use to determine CCPR before sending frequency requests to FAFu.)

6.2.3 Gaseous Absorption

Oxygen and water-vapor molecules absorb energy from radio waves. Gaseous attenuation due to absorption for surface paths is characterized in [13]. The calculation requires surface water-vapor density under non-rain conditions at the midpoint of the path. Gaseous losses are quite small below 6 GHz, so gaseous absorption will not be considered in FAFu unless and until frequencies above 6 GHz become available for CNPC links.

6.2.4 Tropospheric Scatter

A radio wave can be scattered because of irregularities in air density. This phenomenon is called tropospheric scatter (or troposcatter) propagation. It happens only in the troposphere and is caused mainly by forward scattering from turbulence in a common volume where transmitting and receiving antenna beams intersect above a mutual radio horizon that they view from opposite sides. Interference via troposcatter is likely to occur only when the transmitter has a high EIRP and the receiving antenna is directional.

The troposcatter propagation loss model in [6, Atch. E] is a function of operational frequency, path length, scatter angle, and meteorological and atmospheric-structure parameters. The path loss rises dramatically as scatter angle increases. The scatter angle is the sum of the angles of the transmitting and receiving antenna beams above the horizon, plus the angle subtended by the propagation path as seen from the center of the earth.

6.3 Combined Terrain and Atmospheric Loss

The FAFu propagation model will combine the predictions of the various P.2001 submodels discussed above to predict the additional propagation loss L_{au} that will be exceeded all but T_{pc} percent of the time (where T_{pc} is a nationwide CSA-specified value such as 0.2%) along the undesired-signal path being analyzed. According to [6, p.2], the P.2001 model's range of applicability is as follows:

- Frequency can range from 30 MHz to 50 GHz.
- There is no specific minimum or maximum path length, but the model is believed to be most reliable for distances between 3 and 1000 km (about 1.6–540 nmi). At shorter distances, the effect of clutter (buildings and trees) tends to predominate unless the path is unobstructed.
- There is no firm limit on antenna height, but the method is believed to be most reliable for antenna heights up to 8000 m (about 26,000 feet AMSL).

Figure 6-11 shows the overall structure of the propagation model. It encompasses a complementary set of propagation modules ensuring that the predictions consider all the significant interference-propagation mechanisms that can arise. Blue boxes indicate the inputs that must be provided by users. Green boxes show digital databases available to FAFu. The other boxes represent submodels that receive and process the input data. The rain-loss module will not be included in the initial version of FAFu, but may be added later.

The two most important submodels—ducting and diffraction—are fully correlated, so the following method is used to combine the loss predictions for diffraction and ducting [6, Atch. J]. The two submodels are combined power-wise at the time percentage T_{pc} to give an overall propagation loss, L_{bm12}, which is calculated as follows. Let L_{bm1} be the calculated total propagation loss for a rough-earth path (i.e., the sum of L_{pu} (D_u) and L_{au} (T_{pc})), with atmospheric effects not considered. Let L_{ba} be the calculated total propagation loss for atmospheric ducting effects, with terrain not considered. Set L_m to the smaller of those two basic transmission losses, L_{bm1} and L_{ba}. Then compute the combined propagation loss as

$$L_{bm12} = L_m - 10 \log \left[10^{-0.1(L_{bm1}-L_m)} + 10^{-0.1(L_{ba}-L_m)}\right] \ \text{dB}. \tag{6-6}$$

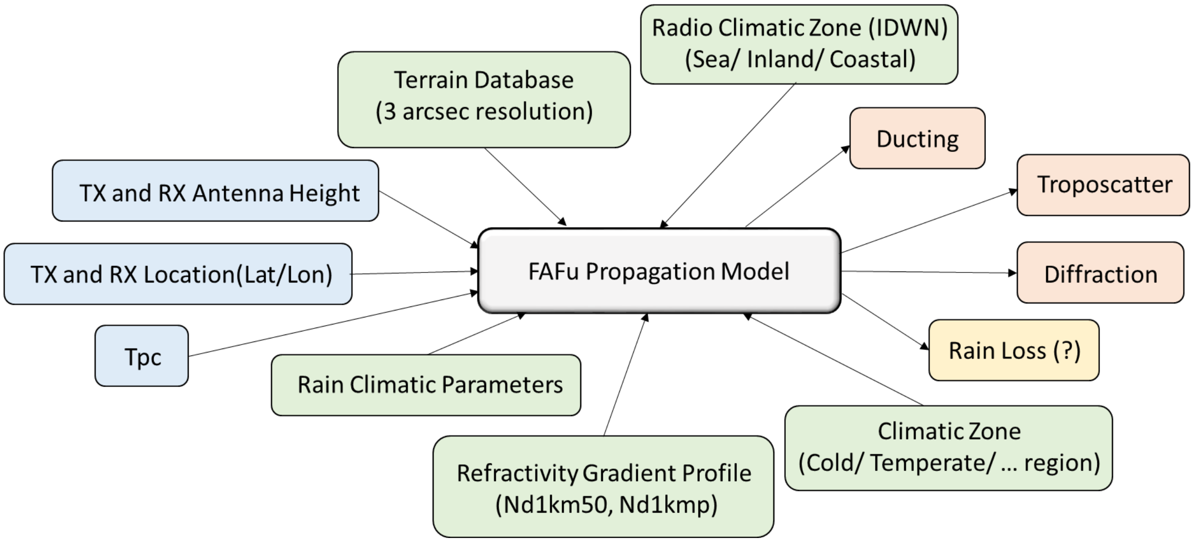


Figure 6-11. Propagation-Model Data Sources and Submodels

The next two figures illustrate an example of propagation predictions obtained using the combined P.2001 terrain and atmospheric models for a particular signal path over mountainous terrain. Figure 6-12 displays the terrain profile for the path. Figure 6-13 shows the predicted loss distributions at 5 GHz. The combined loss is shown as a purple dotted curve. In this example, the free-space loss is 145 dB and the excess loss caused by diffraction is 24 dB at T_{pc} = 50%. Here the diffraction loss dominates the total loss, which leads to L_{bm12} = 169 dB at T_{pc} = 50% (i.e., median path loss). For a lower T_{pc} value such as 0.2%, which the CSA is more likely to establish to provide reasonable protection against RFI, L_{bm12} is clearly much lower, close to the free-space loss.

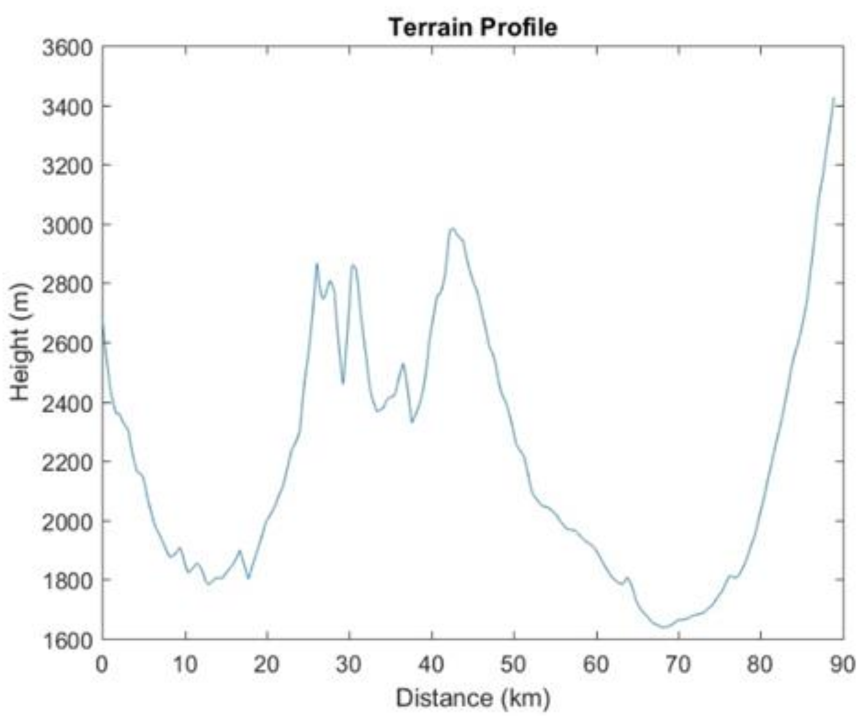


Figure 6-12. Example of Mountainous Terrain Profile

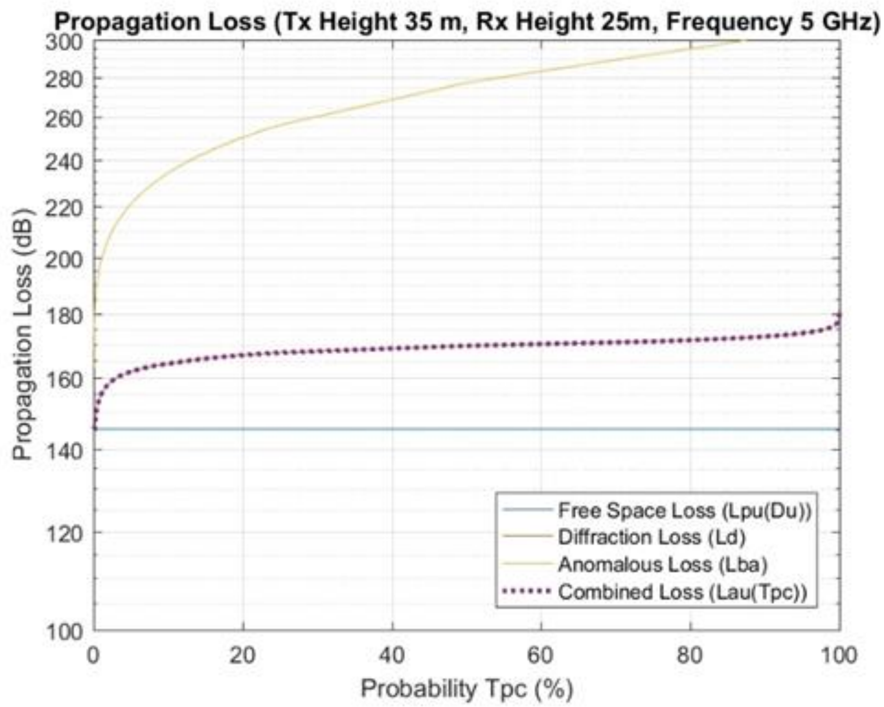


Figure 6-13. Example of Propagation Losses over Mountainous Terrain

Table 6-1 presents P.2001 propagation predictions for a different example that involves relatively flat terrain: a 178-nmi path between a GR in Miami, FL, whose antenna height is 50 feet AGL, and a UA over Tampa, FL. On a standard 4/3 earth, the maximum RLOS distance would not exceed 132 nmi even at the maximum UA altitude of 10,000 feet AGL. The T_{pc} = 50% (median path loss) results in the table reflect that fact, with total path-loss values for that UA altitude about 40 dB above free-space values. But for smaller values of T_{pc} such as 0.2%, the predicted path loss can drop *below* free-space values.

These results underscore the need for probabilistic path-loss predictions to ensure adequate protection against RFI in CNPC links whose required link availabilities may be as high as 99.8% (which would justify use of T_{pc} values on the order of 0.2%). Reliance on the 4/3-earth radio horizon, or on median path-loss values, seems insufficient to protect high-availability CNPC links against RFI.

Table 6-1. P.2001 Predictions for 178-nmi Path from GR in Miami to UA over Tampa

Frequency (MHz)	1105		5060.5	
UA Altitude (feet AGL)	1,000	10,000	1,000	10,000
4/3-Earth Horizon Distance (nmi)	47.6	131.7	47.6	131.7
Free-Space Loss (dB)	144	144	157	157
Path-Loss Value (dB) Predicted to Equal or Exceed Actual Value:				
T_{pc} = 50% of the time	227	182	248	197
T_{pc} = 20% of the time	185	150	206	165
T_{pc} = 2% of the time	148	141	170	156
T_{pc} = 0.2% of the time	140	138	162	152
T_{pc} = 0.02% of the time	137	135	158	150
T_{pc} = 0.002% of the time	134	133	156	148

7 Data Elements Needed for Processing Frequency Requests

To process requests for CNPC frequency assignments, FAFu must maintain and continually update a database of preexisting assignments. The assignment database must contain data on the locations and physical characteristics of all transmitting and receiving equipment in the frequency band(s) of interest, including the equipment belonging to the UAS whose CNPC frequency request is currently being processed. This section identifies key input and output data elements used by FAFu in processing frequency requests.

7.1 Input Data Elements

Assignment records are of two kinds: CNPC link records whose frequency assignments can be made or changed by the CSA on the recommendation of FAFu; and non-CNPC records (e.g., navaids) whose assignments FAFu regards as unchangeable.

7.1.1 Input Data Elements for CNPC Assignment Records

Each CNPC frequency request that FAFu receives must be accompanied by:

1. General link information
2. Ground-station parameters
3. Service-volume parameters
4. Uplink and downlink frequency resources available to the link.
5. Spectral masks (unless already in the FAFu database)
6. Antenna masks (unless already in the FAFu database).

The tables of this section specify the data elements for each class of information, using the following notation:

- In the “Fields” columns, “ID” means “identifier.”
- In the “Format” columns, “char *n*” means “*n* alphanumeric characters,” “int” means “integer,” “float” means “floating-point number,” and UTC means Coordinated Universal Time.
- A dash in a “Units” column means units are unnecessary for or inapplicable to the field under consideration.
- “Any” in an “Allowed Values” column means any properly formatted entry is acceptable unless it would cause an overflow or underflow error.
- “Automatic” in an “Allowed Values” column means FAFu automatically assigns the value for the field under consideration.
- “Preexisting” in an “Allowed Values” column means the referenced transmitter, receiver, or antenna mask being referenced is already in FAFu’s ETC database.

Whenever a frequency request contains a data field with an improper format or a non-allowed value, FAFu immediately notifies the applicant that clarification will be necessary before the request can be processed.

Table 7-1 identifies data fields associated with the CNPC link as a whole, as well as the parameters of the airborne radio and its antenna (which is always assumed to be omnidirectional). Channel widths are specified in tenths of kilohertz for consistency with the units employed later in identifying frequency resource lists.

Table 7-1. General Link Information

Field	Format	Units	Allowed Values	When Used
User ID	char 18	—	Preassigned	Always
Serial number of request	int	—	Automatic	Always
Requested start date and time	UTC	—	Any	Always
Requested end date and time	UTC	—	Any	Always
Link category	char 1	—	S = SF; D = DF	Always
DO-362 compliance indicator	char 1	—	Y = compliant; N = not	Always
Uplink channel width	int	Tenths of kHz	Positive multiples of 50	Always
Downlink channel width	int	Tenths of kHz	Positive multiples of 50	Only when link category = D
Uplink signal polarization	char 1	—	H = horizontal V = vertical C = circular R = right-hand circular L = left-hand circular O = other or unspecified	Always
Downlink signal polarization	char 1	—	H = horizontal V = vertical C = circular R = right-hand circular L = left-hand circular O = other or unspecified	Always
Number of GSs supporting the link	int	—	≥ 1	Always
ID of first supporting GS	char 18	—	Any	Always
…	…	…	…	…
ID of *n*th supporting GS	char 18	—	Any	Only when > 1 supporting GS
…	…	…	…	…
ID of last supporting GS	char 18	—	Any	Only when > 1 supporting GS
SV ID	char 18	—	Any	Always
Airborne transmitter power	float	watts	≥ 0	Always
Airborne transmitter mask number	int	—	> 0; preexisting or automatic	Always
Airborne transmitting antenna’s maximum gain	float	dBi	Any	Always
Airborne receiving antenna’s maximum gain	float	dBi	Any	Always
Airborne receiver mask number	int	—	> 0; preexisting or automatic	Always
Airborne receiver sensitivity	float	dBm	Any	Always
Airborne receiver CCPR	float	dB	Any	Always
Remarks	text	—	Any	Optional

Table 7-2 identifies data that FAFu needs on *each* GS that supports the CNPC link.

Table 7-2. Ground-Station Parameters

Field	Format	Units	Allowed Values	When Used
GS ID	char 18	—	Any	Always
Site name	char 26	—	Any	Always
State abbreviation	char 2	—	Postal abbreviations	Always
Latitude	float	degrees	0 to 90 in N Hemisphere; –90 to 0 in S	Always
Longitude	float	degrees	0 to 180 in E Hemisphere; –180 to 0 in W	Always
Site elevation AMSL	integer	feet	≥ –1500	Always
Antenna height AGL	integer	feet	≥ 0	Always
Transmitter power	float	watts	≥ 0	Always
Transmitter mask number	int	—	> 0; preexisting or automatic	Always
Transmitting antenna’s maximum gain (minus any installation losses)	float	dBi	Any	Always
Transmitting antenna’s mask number	int	—	≥ 0 (0 = omnidirectional); preexisting or automatic	Always
Transmitting antenna’s azimuthal-steerability indicator	char 1	—	F = fixed L = limited A = all directions	Only when mask number > 0
Transmitting antenna’s CCW steerability limit, measured clockwise from true north	float	degrees	Nonnegative value < 360	Only when steerability indicator = F or L
Transmitting antenna’s CW steerability limit, measured clockwise from true north	float	degrees	Nonnegative value < 360	
Receiving antenna’s maximum gain (minus any installation losses)	float	dBi	Any	Always
Receiving antenna’s antenna mask number	int	—	≥ 0 (0 = omnidirectional); preexisting or automatic	Always
Receiving antenna’s azimuthal-steerability indicator	char 1	—	F = fixed L = limited A = all directions	Only when mask number > 0
Receiving antenna’s CCW steerability limit, measured clockwise from true north	float	degrees	Nonnegative value < 360	Only when steerability indicator = F or L
Receiving antenna’s CW steerability limit, measured clockwise from true north	float	degrees	Nonnegative value < 360	
Receiver mask number	int	—	> 0; preexisting or automatic	Always
Receiver sensitivity	float	dB	Any	Always
Receiver CCPR	float	dB	Any	Always
Remarks	text	—	Any	Optional

Table 7-3 specifies parameters that describe the service volume in which the UA flies. The fields of interest differ with SV shape. In the case of PSVs (SVs whose horizontal cross sections are polygonal), the latitudes and longitudes of all vertices must be specified in vertex-connectivity order (i.e., a segment of the polygon connects vertices *n* and *n* + 1 for all *n*, and also connects the last vertex with the first vertex).

Table 7-3. Service-Volume Parameters

Field	Format	Units	Allowed Values	When Used
SV ID	char 18	—	Any	Always
SV ceiling altitude type	char 1	—	G = AGL S = AMSL	
SV ceiling altitude	int	feet	≥ 0 if AGL	
SV floor type	char 1	—	G = AGL S = AMSL	
SV floor altitude	int	feet	≥ 0 if AGL	
SV shape	char 1	—	C = circular P = polygonal	
CSV center's latitude	float	degrees	0 to 90 in N Hemi-sphere; –90 to 0 in S	Only when SV shape = C
CSV center's longitude	float	degrees	0 to 180 in E Hemi-sphere; –180 to 0 in W	
CSV radius	float	nmi	≥ 0	
Number of vertices in PSV cross section	int	—	3–150	Only when SV shape = P
Latitude of first vertex	float	degrees	0 to 90 in N Hemi-sphere; –90 to 0 in S	
Longitude of first vertex	float	degrees	0 to 180 in E Hemi-sphere; –180 to 0 in W	
…	…	…	…	
Latitude of *n*th vertex	float	degrees	Same as for first vertex	
Longitude of *n*th vertex	float	degrees	Same as for first vertex	
…	…	…	…	
Remarks	text	—	Any	Optional

Table 7-4 identifies input data fields used in specifying lists of assignable center frequencies for uplink and downlink channels. The units are tenths of kilohertz because DO-362 allows assignable frequencies to be multiples of 2.5 kHz. Every frequency that the user enters into an uplink (or downlink) resource list must be separated by at least half the uplink (or downlink) channel width from the nearest end of the frequency range (e.g., 1040–1080 MHz) being used, to ensure that every part of an assigned channel will lie within authorized CNPC spectrum.

Table 7-4. Frequency-Resource Information

Field	Format	Units	Allowed Values	When Used
Number of frequency ranges in uplink resource list	int	—	1–100	Always
Uplink frequency increment	int	Tenths of kHz	Positive multiples of 50	
First frequency in first uplink range	int	Tenths of kHz	Positive multiples of 25	
Last frequency in first uplink range	int	Tenths of kHz	First frequency in range, plus positive multiple of uplink increment	
…	…	…	…	
First frequency in *n*th uplink range	int	Tenths of kHz	Positive multiples of 25	
Last frequency in *n*th uplink range	int	Tenths of kHz	First frequency in range, plus positive multiple of uplink increment	
…	…	…	…	
Number of frequency ranges in downlink resource list	int	—	1–100	Only when link category = D
Downlink frequency increment	int	Tenths of kHz	Positive multiples of 50	
First frequency in first downlink range	int	Tenths of kHz	Positive multiples of 25	
Last frequency in first downlink range	int	Tenths of kHz	First frequency in range, plus positive multiple of downlink increment	
…	…	…	…	
First frequency in *n*th downlink range	int	Tenths of kHz	Positive multiples of 25	
Last frequency in *n*th downlink range	int	Tenths of kHz	First frequency in range, plus positive multiple of downlink increment	
Remarks	text	—	Any	Optional

If the link category is S (single-frequency), only the uplink frequency range(s) are to be specified, because in that case the link will be using the same frequency for downlink as well as uplink transmissions, and FAFu will take that into account when screening candidate frequencies for interference problems. However, if the link category is D (dual-frequency), then one or more separate downlink frequency ranges must be specified, although the two sets of frequency ranges can overlap or even be identical if the user wishes.

Table 7-5 identifies fields used to define spectral masks for transmitters and/or receivers. As noted earlier, the mask is considered symmetrical around the tuned frequency, so the user enters only points on the right side of the mask, where the frequency difference from the tuned frequency is nonnegative. The first point must correspond to the tuned frequency, where frequency difference and attenuation are both zero. Thereafter, attenuation must monotonically increase with frequency difference. The user does not need to provide the information in the table if the parameters of the mask being referenced are already in FAFu's ETC database.

Table 7-5. Spectral-Mask Parameters

Field	Format	Units	Allowed Values	When Used
Mask number	int	—	> 0; automatic	Always
Number of points to be specified on right side of mask	int	—	2–251	Always
Frequency difference of first point	float	kHz	0	Always
Attenuation at first point	float	dB	0	Always
…	…	…	…	…
Frequency difference of *n*th point	float	kHz	≥ frequency difference of (n – 1)th point	Always
Attenuation at *n*th point	float	dB	≥ attenuation of (n – 1)th point	Always
…	…	…	…	…
Remarks	text	—	Any	Optional

Table 7-6 identifies fields used to define azimuthal masks for directional ground-station antenna patterns. The mask is considered to be symmetrical around boresight, so the user enters only points on the CW side of the mask. The first point must be at boresight, where off-axis angle is zero. Thereafter, attenuation must monotonically increase with off-axis angle.

Table 7-6. Directional Antenna-Mask Parameters

Field	Format	Units	Allowed Values	When Used
Mask number	int	—	> 0; automatic	Always
Number of points to be specified on CW side of mask	int	—	2–100	Always
Off-axis angle of first point	float	degrees	0	Always
Attenuation at first point	float	dB	0	Always
…	…	…	…	…
Off-axis angle of *n*th point	float	degrees	≥ off-axis angle of (n – 1)th point	Always
Attenuation at *n*th point	float	dB	≥ attenuation of (n – 1)th point	Always
…	…	…	…	…
Remarks	text	—	Any	Optional

There is no need to create an antenna-mask record for an omnidirectional antenna. FAFu assumes all airborne antennas are omnidirectional, with mask numbers of 0. An omnidirectional ground antenna is given a mask number of 0 when its GS record is set up. FAFu assumes every antenna with a mask number of 0 has a pattern attenuation of 0 dB in all directions. Even if a GS antenna is directional, the user does not need to provide the information in Table 7-6 if the parameters of the antenna mask being referenced are already in the ETC database.

7.1.2 Input Data Elements for Non-CNPC Assignment Records

In some frequency bands and geographical regions, CNPC links may need to coexist with other kinds of RF systems such as DME or MLS. FAFu will not recommend frequency changes to non-CNPC systems but must be given data on their existing assignments to ensure their compatibility with the CNPC assignments it recommends. Maintaining a database of preexisting non-CNPC assignments is the responsibility of the CSA, which can obtain the data from the National Telecommunications and Information Administration (NTIA) and Federal Communications Commission (FCC). The data elements are generally the same as for CNPC frequency requests, except that (a) the frequencies are preassigned instead of being selectable by FAFu, and (b) for systems such as navaids that use absolute interference thresholds (in dBm) rather than ratio-based assignment criteria, those thresholds are used instead of CCPRs in the assignment records.

7.2 Output Data Elements

Table 7-7 shows the structure of the assignment message that FAFu sends to inform a UAS that its request for a CNPC frequency assignment has been granted.

Table 7-7. FAFu Assignment-Message Structure

Field	Format	Units	Allowed Values	Remarks
User ID	char 18	bytes	Preassigned	
Serial number of request	int	—	Preassigned	
Start date and time of assignment	UTC	—	Chosen by applicant	
End date and time of assignment	UTC	—	Chosen by applicant	
Link category	char 1	—	Chosen by applicant: S = single-frequency, or D = dual-frequency	
Uplink channel width	int	Tenths of kHz	Positive multiple of 50 (chosen by applicant)	If link category = S, these parameters also apply to the downlink.
Assigned uplink frequency (center frequency of FAFu-assigned uplink channel)	int	Tenths of kHz	Any frequency belonging to a user-specified uplink frequency resource list	
Downlink channel width	int	Tenths of kHz	Positive multiple of 50 (chosen by applicant)	These fields are used only when link category = D.
Assigned downlink frequency (center frequency of FAFu-assigned downlink channel)	int	Tenths of kHz	Any frequency belonging to a user-specified downlink frequency resource list	
Remarks (including any necessary restrictions on the use of the assigned frequency, such as exclusion zones around the locations of potential RFI sources or victims)	text	—	Any	Optional

8 Methods for Rapid Selection of Compatible Frequencies

This section describes methods that FAFu's algorithms will employ to minimize running time and conserve spectrum while achieving the overarching goal of spectral coexistence among all users of a CNPC frequency band.

8.1 Preliminary Screening of Interference Cases

FAFu will save a great deal of running time by eliminating a given transmitter-receiver pair from consideration as a potential interference case whenever *any* of the following conditions applies:

- The undesired transmitter and the receiver are both DO-362-compliant GRs and the path length of the undesired signal does not exceed that of the receiver's desired signal by more than 210 nmi, so that (as explained in Section 3.3) the DO-362 TDD scheme precludes ground-to-ground RFI.
- The undesired transmitter and the receiver are both DO-362-compliant ARs and the path length of the undesired signal does not exceed that of the desired signal by more than 437 nmi, so (as noted in Section 3.3) the TDD scheme precludes air-to-air RFI.
- An undesired signal traversing *any* possible propagation path between the transmitter and receiver has less than a T_{pc} percent chance of exceeding the receiver's CCPR or interference threshold, even with worst-case antenna orientations, the largest possible value of desired-signal path length D_d, and the smallest possible value of D_u given the locations of the transmitter, the receiver, and their SVs. T_{pc} is a value of acceptable interference probability, perhaps 0.2%, to be determined by the CSA and used on a nationwide basis. Applying this test would require the prior existence of an automated library, which could be compiled by the CSA, containing results of many previous runs of the FAFu propagation model in various frequency bands in all locales within the U.S., and compiled in a form allowing table lookup of worst-case (minimum) undesired-signal path loss as a function of D_u, frequency band, and T_{pc}.

8.2 Calculating Propagation Loss along Multiple Paths

In situations where a very large number of undesired-signal propagation paths need to be evaluated between a single GR and another UAS's SV (as shown in Figure 3-7) or between two SVs, FAFu will employ parallel processing if necessary to keep running times manageable.

8.3 General Frequency-Assignment Strategy

- Since integer arithmetic is much more time-efficient than floating-point calculations, FAFu will store all frequencies (including widths and boundaries of channels) as integers, and will use integer arithmetic whenever it adds, subtracts, or compares frequencies during a run.
- FAFu will expedite the process of weeding out each new CNPC link's unusable candidate frequencies by considering one potential interferer at a time, rather than by checking the link's list of candidate frequencies one by one. This is faster because a single interferer can block the use of many frequencies within the new link's resource list, whereas checking one frequency at a time would necessitate revisiting the entire list of potential interferers over and over.

- After completing the winnowing of each CNPC link's candidate frequency list, FAFu will assign to the link the surviving frequency that is closest to a "concentration point" (at either end of the band or perhaps somewhere in the middle) that has been designated by the CSA. This conserves spectrum because, as past studies (e.g., [14]) have shown, packing frequency assignments as close as possible to a predetermined concentration point in a band tends to maximize the number of links that can be given interference-free assignments before the band becomes so congested that it becomes necessary to start denying frequencies to some new requesters.
- When checking for intermodulation problems, FAFu will utilize the fact that most of the IMPs generated by transmitters within bands as narrow as those available to CNPC fall outside those bands and thus do not affect CNPC receivers. For example, transmitters in the 5030–5091 MHz band can generate IMPs of the form $2f_1 - f_2$ that fall within the band and thus could affect receivers in that band. But IMPs of the form $2f_1 + f_2$ cannot, and so would not need to be checked. FAFu will use a simple formula provided in [15] for screening out irrelevant IMPs.

8.4 Neighbor-Repacking

FAFu will have a "neighbor-repacking" capability enabling it—if no other option seems available to find a frequency for a new link, and only with permission from the CSA—to look for opportunities to create spectral "room" for the new link by retuning one or more preexisting links. With this capability, if FAFu is initially unable to assign link A to a particular frequency because of conflicts with the preexisting "blocking" assignments of neighboring links B, C, and D, the program can check to see if there is any way to reassign B, C, and D to other frequencies to make room for a conflict-free assignment of A to the frequency in question. In situations where B, C, and/or D cannot be reassigned without causing interference, FAFu can also explore the possibility of breaking the logjam by changing some other preexisting assignment (to link E, say) that is blocking the reassignment of B, C, or D. This process can continue until it reaches the deepest reassignment "layer" that the CSA allows FAFu to probe. Figure 8-1, adapted from [3], depicts this succession of link reassignments as a multilayered "reassignment tree."

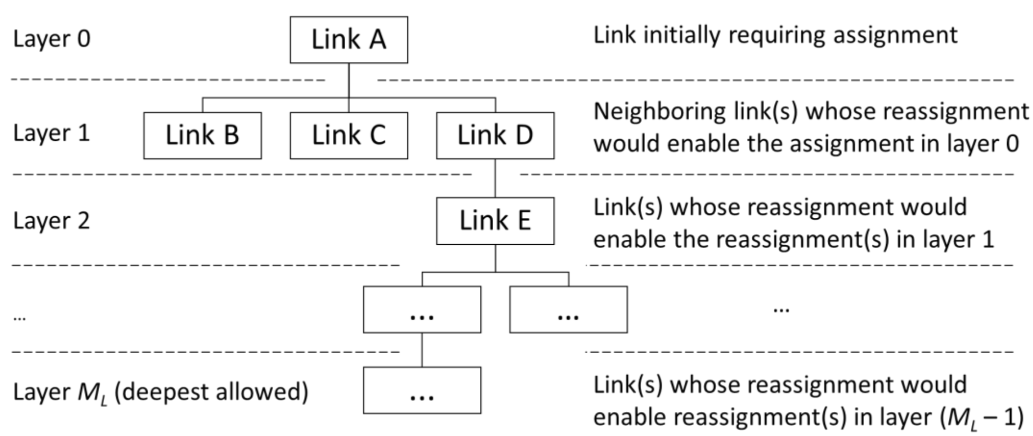


Figure 8-1. Example of a Reassignment Tree

9 Potential Future Enhancements

This section describes three potential enhancements to FAFu that could become useful in the future as CNPC link assignment and deployment procedures evolve. Each of the enhancements would involve changes to some of the FAFu algorithms and data structures described in this report. The possible enhancements would be needed for the following contingencies:

- The use of time-division multiple access (TDMA) to enable multiple CNPC links to operate on a single shared frequency
- The use of CNPC spectrum for point-to-point relays between pilot and UA ground sites
- The use of CNPC spectrum by very-high-altitude UA.

9.1 Time-Division Multiple Access

TDMA allows multiple links to share a single frequency by using designated, mutually exclusive time slots. RTCA SC-228 is exploring the possibility of adding TDMA capabilities to the DO-362 specification. Besides potentially reducing the amount of ground infrastructure to support UAS operations at airports, TDMA also offers a possible means for alleviating “near/far” RFI problems that can arise among neighboring CNPC links whose transmitters have high noise floors.

FAFu can be upgraded to allow it to assign frequencies to ad hoc groups of UAS sharing a single frequency by using separate TDMA time slots, but the details of the TDMA approach to be used will have to be well-defined. TDMA schemes can be categorized according to time-slot duration and/or the number of participating ground stations.

- The UAS group employing a single TDMA frequency may share a single GR, or there may be multiple GRs at separate locations.
- The time slots can be fractions of the 50-ms TDD frame duration, or can encompass multiple TDD frames. In the latter case, each participating link might use every second, third, or fourth frame and remain silent during other frames.

The number of time slots per TDD frame is important because the geographical size of a TDMA group is limited not only by propagation losses but also by time delays resulting from the finite velocity of radio waves. The arrival time of a radio signal moving at the speed of light is delayed 1.0 ms for every 161.879 nmi the signal travels. A message transmitted on a particular time slot may reach a receiver so late that part of it spills into an adjacent time slot, causing excess-delay interference (EDI).

EDI can occur between adjacent slots in a given uplink or downlink frame, or between adjacent uplink and downlink frames. To protect against EDI, an interslot “guard time” must be built into the system architecture. The guard time constitutes an upper bound on acceptable propagation delay within the group. The applicable value of this parameter for a particular TDMA group depends on the number of available slots and the desired maximum geographical extent of the group. Figure 9-1 shows plan views of possible paths between GRs (represented by squares) and UA (depicted as circles) in a group of two CNPC links. The polygonal SV boundary of each link is also shown.

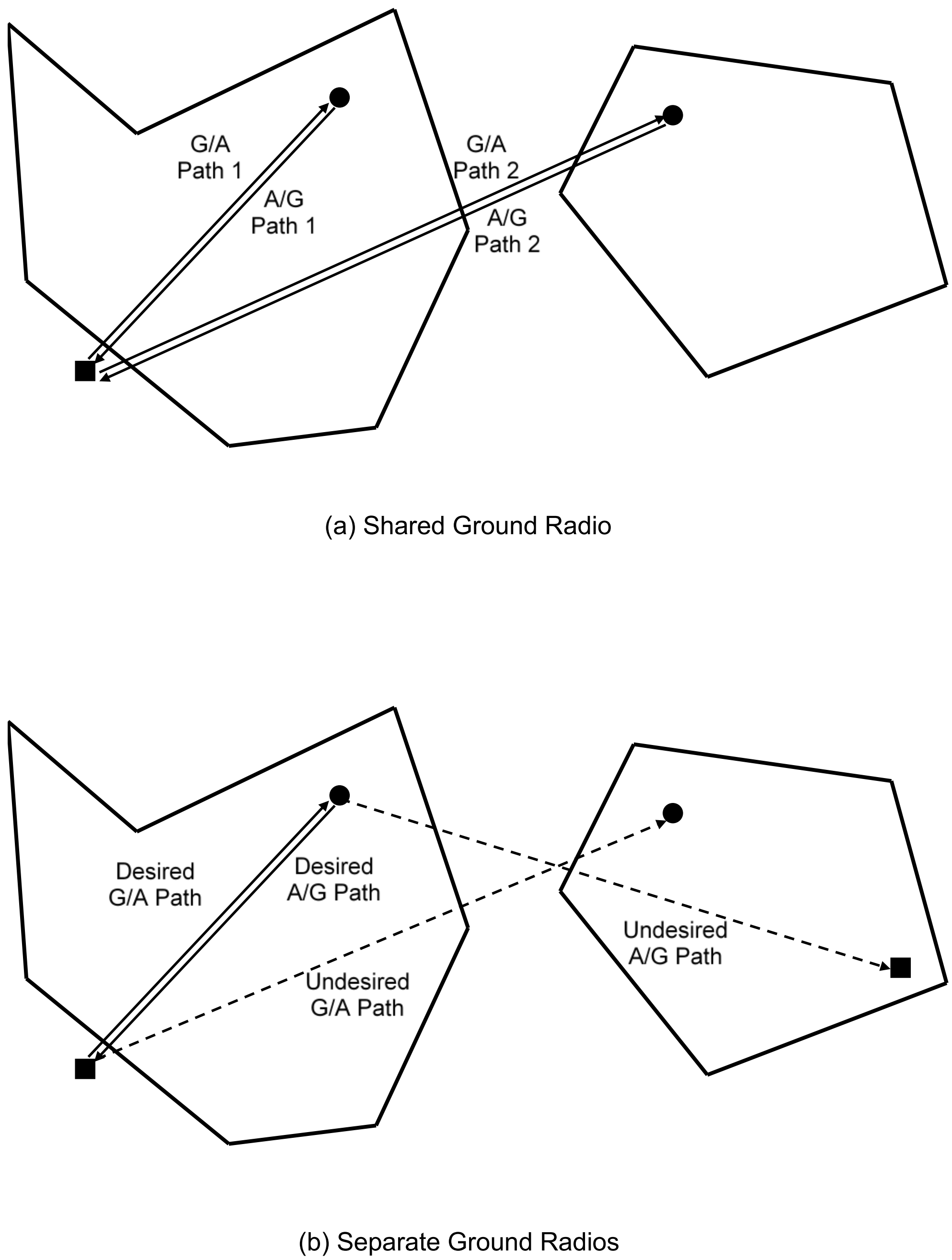


Figure 9-1. Signal Paths in a Two-Link TDMA Group

When the links share a common GR, the scenario of Figure 9-1(a) applies. The shared GR exchanges signals with each UA in their links' respective time slots. Each signal's arrival at a UA is delayed in proportion to the length of the path it traverses. The delay must not exceed the guard time, or EDI could result. FAFu must ensure that the worst-case (i.e., largest) path length for the UA under consideration does not exceed a "maximum TDMA distance" determined by the guard time. If it does, FAFu must refuse permission to add the UAS to the TDMA bundle.

Figure 9-1(b) shows the desired signal paths for each link, and the undesired paths along which EDI can propagate from the link on the left to the one on the right, in a situation where the links use separate GRs. (The left-hand link also must be protected against EDI from the right-hand link, but those relationships are not shown in the figure.) In this situation, FAFu must check the lengths of the undesired signal paths as well as the desired ones.

These and other issues must all be considered in upgrading FAFu to manage time slots and frequencies within a TDMA-enabled system.

9.2 Point-to-Point Ground Relays

In many situations, beyond-line-of-sight (BLOS) links will be necessary between a pilot and a UA whose service volume is in a remote location. If no commercial network is available to provide connectivity, it may be advantageous to use DO-362-compliant point-to-point relays as depicted in Figure 9-2. In this example the pilot and UA are connected by one relay, two point-to-point links, and a regular air/ground CNPC link. Being DO-362-compliant, all three links use TDD and so need only a single frequency each. Dual-frequency links could be used instead, but that would double the number of frequencies needed, although the channel width needed for each frequency might be less. Since the present FAFu specifications allow only for air/ground radio links, modeling such relays in FAFu would require changes in the specifications to allow ground stations with directional antennas to communicate with one another. Two new link categories would need to be defined: single-frequency point-to-point, and dual-frequency point-to-point.

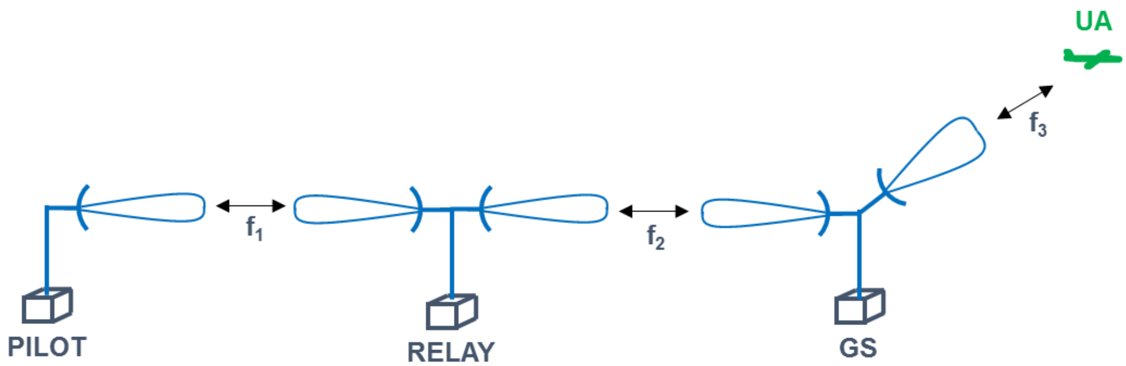


Figure 9-2. Point-to-Point CNPC Ground Relay

9.3 Very-High-Altitude UA

The advent of very-high-altitude UA (VUA) systems (VUAS) may also require modification to the FAFu paradigm. Figure 9-3 illustrates a possible scenario, in which a VUA hovering between 60,000 and 100,000 feet AMSL is visible to a not-very-high UA (NUA) and the GS of the short-range NUA system (NUAS) to which the NUA and its GS both belong. The direct paths from the VUAS GS to the NUA and its GS are both blocked by terrain or earth curvature, so that only the interference path shown in the figure is relevant.

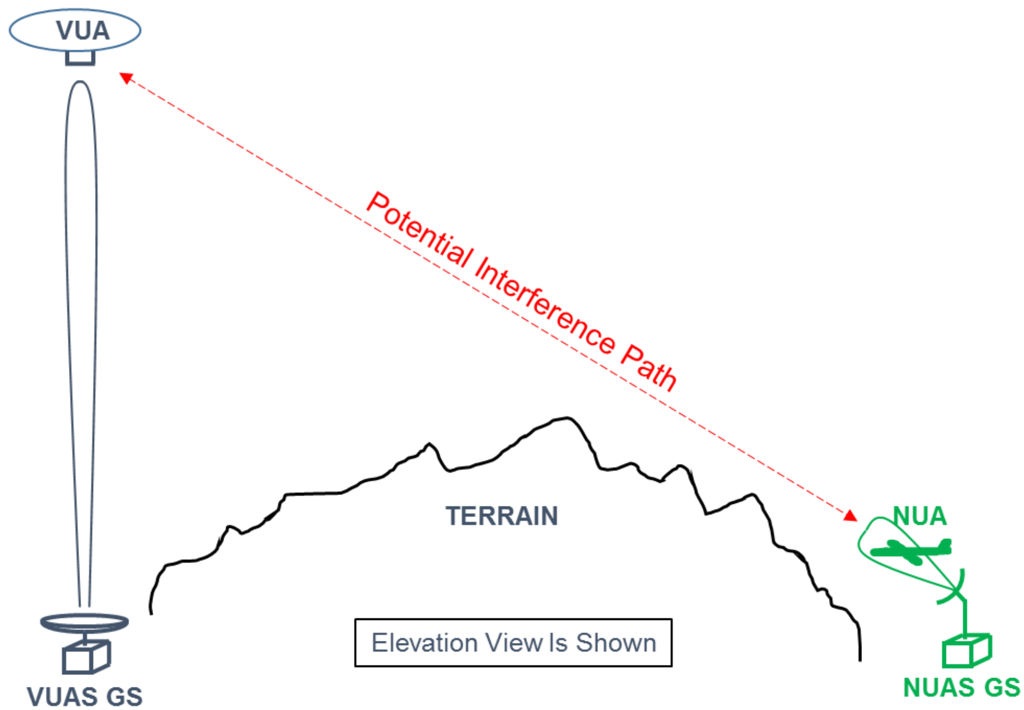


Figure 9-3. Potential Interference Between VUAS and NUAS

In this scenario the elevation angle of the directional NUAS GS antenna as it tracks the NUA is essential in determining whether the VUA is in the main beam of that antenna and thus capable of causing RFI to the NUAS GS, or susceptible to RFI from it. The fact that the directional VUAS GS antenna is pointed toward the zenith is also relevant to frequency management. However, the two-dimensional antenna model described in Section 5 deals only with azimuthal antenna patterns and angles. To model such scenarios adequately, it may be necessary to upgrade the FAFu antenna model to consider vertical-plane antenna-pattern masks as well as the horizontal-plane pattern masks described in Section 5. Moreover, the VUA itself may have a directional CNPC antenna, probably directed toward the VUAS GS at its nadir, so FAFu would need to be enabled to model directional antennas on UA, not just omnidirectional UA antennas as in the present plan.

10 Phased Implementation Plan

The timeline for FAFu implementation will depend strongly on the speed of regulatory approval of the DO-362 standard, and user adoption of radios that are compliant with it. A possible FAFu implementation sequence is outlined below.

<u>Phase 1 (2018–2020)</u>:

- Develop a FAFu prototype that can be used to solve actual CNPC frequency-assignment problems off-line. Prototype will embody key FAFu capabilities:
  - Antenna-directionality effects
  - Undesired-signal loss modeling based on ITU-R P.2001
  - Frequency-dependent rejection of undesired signals
  - Automatic identification and selection of interference-free frequencies
  - User documentation.
- Track ongoing P.2001 validation studies and modify prototype accordingly.
- Develop table of worst-case (minimum) undesired-signal path loss as function of distance, band, and allowable link unavailability (T_{pc}) for FAFu use in preliminary screening of possible interference cases.
- Investigate potential interactions among FAFu, the FAA UAS Integration Office, the FAA Air Traffic Organization, the FAA Spectrum Office, the Department of Defense, and non-Government entities.
- June 2020: Publication of DO-362 Revision A (expected to include TDMA).

<u>Phase 2 (2020–2022)</u>

- Prototype verification and validation. Use FAFu off-line to recommend frequency assignments for experimental CNPC links at test centers.
- Upgrade prototype to handle TDMA, point-to-point links, and VUAS CNPC links.
- Develop remote-access capability with user interface and security features.
- Decide what organization will run the Central Spectrum Authority (CSA) and FAFu.

<u>Phase 3 (2022–2025)</u>

- Use FAFu to make 10–100 CNPC frequency assignments per day, with 1–2 day turnaround, for UAS operating in controlled airspace.
  - On-line user data entry
  - Semiautomatic FAFu operation with frequent manager intervention.

<u>Phase 4 (2025–)</u>

- Use FAFu to make 100–1000 near-real-time CNPC frequency assignments per day for UAS operating in nonsegregated controlled airspace throughout the U.S.
  - Fully automatic FAFu operation with managerial oversight and occasional intervention.

11 Recommendations

1. A Central Spectrum Authority (CSA) equipped with an automated Frequency Assignment Function (FAFu) should perform nationwide day-to-day management of radio spectrum assets available to the UAS control and non-payload communications (CNPC) links that will be compliant with the RTCA DO-362 standard.
2. Upon receiving requests from UAS operators for radio frequencies to be used by their CNPC links during specific UA flights, the CSA should respond in near-real time. It should use FAFu to identify and assign frequencies that will comply with all applicable interference-prevention rules throughout the flights, provided that the UA remain within their specified service volumes (SVs) and adhere to all other conditions stipulated in the operators' frequency requests.
3. FAFu should calculate minimum allowable frequency separations between new and preexisting frequency assignments on the basis of (a) the predicted desired-to-undesired signal-power ratio at the RF input port of each CNPC receiver that could be affected by the new assignment, and (b) the predicted undesired-signal strength at the RF input port of each potentially affected navaid receiver.
4. When predicting the strengths of signals entering a receiver, FAFu should consider the directionality, steerability, and cross-polarization of transmitting and receiving antennas whenever those parameters are applicable.
5. When predicting the received strength of a *desired* CNPC signal, FAFu should assume it traverses a radio-line-of-sight (RLOS) path with adequate terrain clearance. Each UAS operator should remain responsible for ensuring that such a RLOS path exists throughout the UA's flight.
6. When predicting the received strength of an *undesired* signal, FAFu should conservatively assume a propagation path-loss value (computed using algorithms in ITU-R P.2001 [6]) that will be exceeded during a fraction of time comparable to the required availability of the desired link.
7. FAFu development should proceed in stages, in general accordance with the phased implementation plan outlined in Section 10.

12 References

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Appendix A Use Cases

We have developed several FAFu use cases based on information contained in the CONOPS in Section 2. A use case defines the interactions between a system and its users. Use cases are typically defined for the goals that can be achieved by using the system. They are helpful in defining system functionality and requirements. The primary use case envisioned for the FAFu system, as described in the CONOPS, is that of a UAS operator requesting a CNPC frequency that does not conflict with preexisting assignments. Figure A-1 graphically depicts this use case and related lower-level use cases.

The Request Frequency Assignment use case is a summary-level use case that describes the processing of a user's request for a CNPC frequency. Because it is a summary-level use case, it contains references to lower-level use cases that must be accomplished to complete the request. This structure allows a complex process to be broken into pieces that can be described by their own use cases.

The Request Frequency Assignment use case includes the Input User Data (Text) and Input User Data (Graphical) use cases. These describe how a user can enter data that is needed to assign a frequency for use. The Update Assignment Engine use case describes the subsequent processing needed to send the input data to the Assignment Engine and update its data repository. The Run Assignment Engine use case describes the processing needed to use the input data to assign a frequency for the user. The output of this use case is a frequency that must be evaluated by the FAFu manager.

Two use cases are relevant to the FAFu manager. Before frequencies can be assigned to users, the FAFu manager must start the assignment engine, described in the Start Assignment Engine use case. When the manager is notified of a frequency produced by the Assignment Engine, the manager reviews the frequency assignment and reports it to the user, as described in the Review Assignment Engine Result use case.

Use-case details can be presented in many different forms. The use cases shown in Figure A-1 were further developed using a narrative format described in [16]. These components are summarized in Table A-1. Each FAFu use case is described using this format in the following subsections.

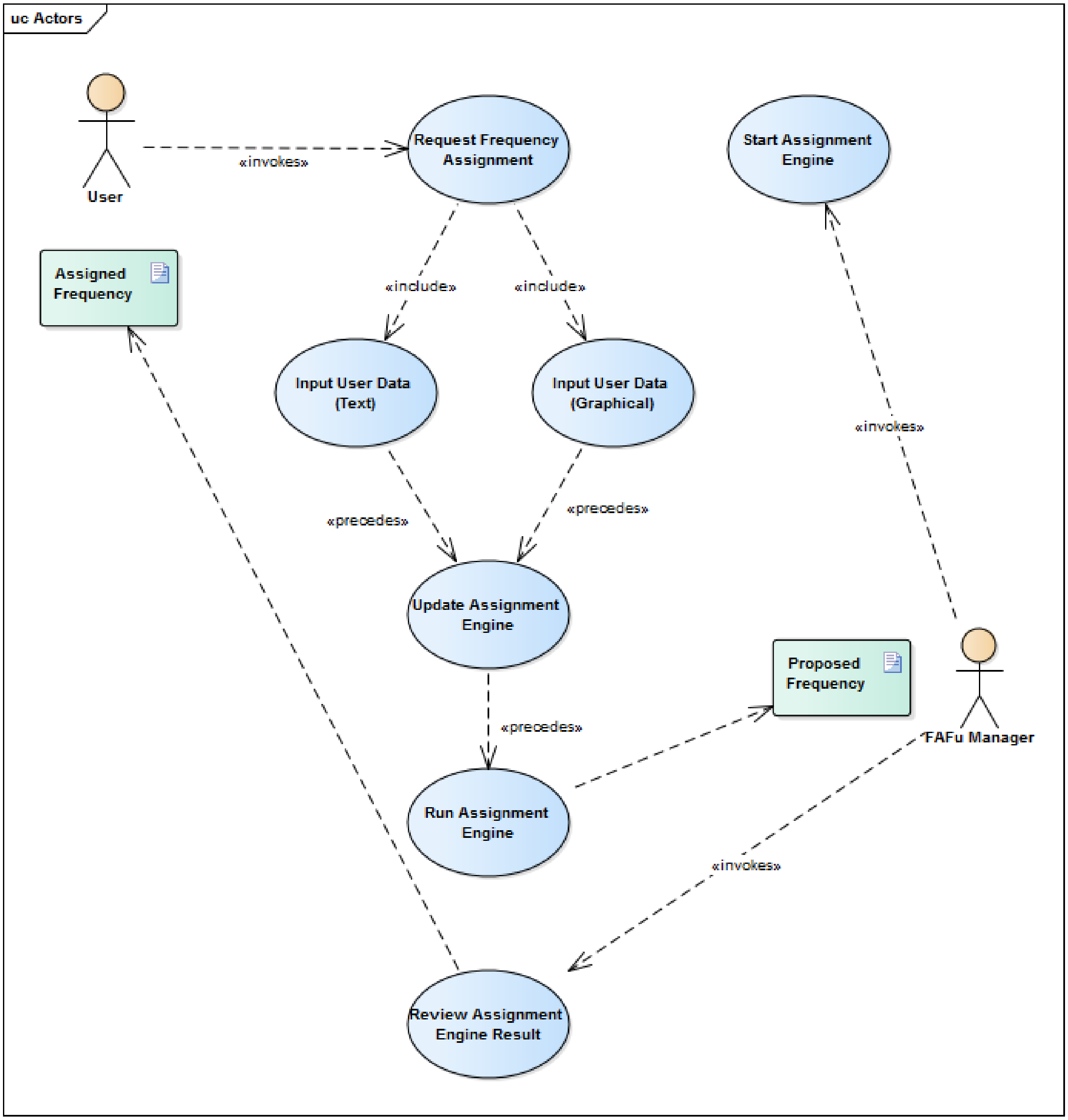

Figure A-1. FAFu Use Case Diagram

Table A-1. Use-Case Components

Component	Description
Use case	Identifying name
Description	Brief description of the use case
Primary actor	Primary person or system interacting with the system being described
Supporting actors	Other people or systems interacting with the system being described
Scope	Definition of the system being described
Level	Summary—High level; provide a context for lower-level goals User goal—Primary goal of the actor when interacting with the system Subfunction—Low level; goals required to accomplish user goals
Stakeholders and interests	People or groups that have an interest in the use case
Preconditions	Requirements that must be satisfied prior to the execution of the use case
Trigger	Event that starts the execution of the use case
Minimal guarantee	Fewest system capabilities that can be delivered when the primary goal cannot be achieved
Success guarantee	Goals satisfied at the successful conclusion of a use case
Main success scenario	Description of the error-free execution of the use case
Extensions	Alternate execution paths
Special requirements	Additional information relevant to the use case
Issues	Comments generated during the review of the use case

A.1 Start Assignment Engine

Use Case: Start Assignment Engine

Description: Assignment Engine is initiated as a server to provide CNPC frequencies upon request.

Primary Actor: FAFu manager

Supporting Actors: None

Scope: Assignment Engine

Level: User goal

Stakeholders and Interests: UAS operators

Preconditions:

1. FAFu manager is authorized to use the system.
2. Data loaded by the Assignment Engine on startup is available:
    a. Preexisting frequency-assignment data, including SV data
    b. Assignment rules
    c. Antenna masks

d. Equipment characteristics
e. Terrain data.

Trigger: FAFu manager initiates the Assignment Engine.

Minimal Guarantee: Conflicting CNPC frequencies are not assigned.

Success Guarantee: Functionality is available to assign non-conflicting CNPC frequencies.

Main Success Scenario:

1. FAFu manager logs in and issues command to start Assignment Engine as a server to receive messages.
2. FAFu manager verifies that the Assignment Engine has started up successfully.

Extensions: None

Special Requirements: None

Issues: None

A.2 Request Frequency Assignment

Use Case: Request Frequency Assignment

Description: Frequency request for a new SV

Primary Actor: User

Supporting Actor: FAFu manager

Scope: FAFu system

Level: Summary

Stakeholders and Interests: UAS operators

Preconditions:

1. User profile on record and user authorized to use FAFu.
2. Necessary data is available:
   a. Data to be entered by user in input data fields
   b. Graphical input of SV data by user
   c. Equipment characteristics data
   d. Antenna-mask data
   e. Assignment rules
   f. Terrain data
   g. Preexisting frequency-assignment data, including SV data
3. The Assignment Engine is initiated as a server.

Trigger: User initiates frequency request.

Minimal Guarantee: Conflicting CNPC frequencies are not assigned.

Success Guarantee: Non-conflicting CNPC frequencies are assigned to users.

Main Success Scenario:

1. User enters data in input fields.
2. User draws the SV on the map.
3. User submits the entered data and receives acknowledgement.
4. The Assignment Engine is updated with the data provided.
5. The Assignment Engine runs and obtains a frequency.
6. FAFu manager reviews the frequency and notifies the user.
7. The frequency request and result are archived.

Extensions:

1. If the Assignment Engine does not obtain a frequency, the FAFu manager can intervene and try to find a frequency.

Special Requirements: None

Issues: None

A.3 Input User Data (Text)

Use Case: Input User Data

Description: User inputs data in fields in a form

Primary Actor: User

Supporting Actors: None

Scope: FAFu client

Level: User goal

Stakeholders and Interests: UAS operators

Preconditions:

1. User profile on record and user authorized to use FAFu.
2. Necessary form and supporting data is available:
    a. Form developed for input and validation of data fields
    b. Necessary data from ETC database
    c. Antenna-mask data.

Trigger: User displays form

Minimal Guarantee: Conflicting CNPC frequencies are not assigned.

Success Guarantee: Text data is ready to be sent to the Assignment Engine.

Main Success Scenario:

1. User enters data in input fields.
2. Data entered is validated.
3. ETC and antenna data needed is present in those files.
4. This data is ready to be merged with the SV data entered on the map.

Extensions: None

Special Requirements: None

Issues: None

A.4 Input User Data (Graphical)

Use Case: Input User Data (Graphical)

Description: User graphically selects SV on aerial map

Primary Actor: User

Supporting Actors: None

Scope: FAFu client

Level: User goal

Stakeholders and Interests: UAS operators

Preconditions:

1. User profile on record and user authorized to use FAFu.
2. Map display and functionality available:
    a. Map routines integrated into input data process.

Trigger: User displays map

Minimal Guarantee: Conflicting CNPC frequencies are not assigned.

Success Guarantee: Graphical data is ready to be sent to the Assignment Engine.

Main Success Scenario:

1. User zooms to area of interest and selects SV graphically.
    a. For a polygon the user selects the boundary points on map.
    b. For a circle the user selects the center and a point to indicate radius on map.
2. The points are converted to a format ready to be merged with other user input data.

Extensions: None

Special Requirements: None

Issues: None

A.5 Update Assignment Engine

Use Case: Update Assignment Engine

Description: Messages to update all frequency request data are prepared and sent to update the Assignment Engine data.

Primary Actor: User

Supporting Actors: None

Scope: FAFu client and Assignment Engine

Level: Subfunction

Stakeholders and Interests: UAS operators

Preconditions:

1. User profile on record and user authorized to use FAFu.
2. User has input all necessary data.
3. The Assignment Engine is initiated as a server.
4. Messages developed containing data to be updated.
   a. Message to update frequency assignment data
   b. Message to update SV data.
5. Software to send messages developed.
6. Software to take data from messages and update Assignment Engine data developed.

Trigger: User submits entered data.

Minimal Guarantee: Conflicting CNPC frequencies are not assigned.

Success Guarantee: User-entered data is sent to the Assignment Engine, which is updated with the new data.

Main Success Scenario:

1. The software inserts the user-entered frequency assignment text data into the message to update the frequency assignment data.
2. The software inserts the user-entered SV data into the message.
3. The message is sent to the Assignment Engine.
4. The Assignment Engine data is updated.

Extensions: None

Special Requirements: None

Issues: None

A.6 Run Assignment Engine

Use Case: Run Assignment Engine

Description: Assignment Engine is run in response to a message requesting a frequency assignment.

Primary Actor: User

Supporting Actor: FAFu manager

Scope: Assignment Engine

Level: Subfunction

Stakeholders and Interests: UAS operators

Preconditions:

1. User profile on record and user authorized to use FAFu.
2. Assignment Engine algorithms revised to take antenna data into consideration.
3. Assignment Engine algorithms revised to take equipment characteristics into consideration.
4. Assignment Engine algorithms revised to take terrain into consideration.
5. Assignment Engine initiated as a server.
6. Assignment Engine has been updated with all needed data entered by user.
7. Software to send message requesting a frequency developed.
8. Software for user to receive return message with frequency or failure developed.

Trigger: Message to run Assignment Engine is sent.

Minimal Guarantee: Conflicting CNPC frequencies are not assigned.

Success Guarantee: Assignment Engine identifies a non-conflicting CNPC frequency and sends notification to the FAFu manager.

Main Success Scenario:

1. Message to run Assignment Engine is sent to Assignment Engine and received.
2. Assignment Engine runs and determines available frequency.
3. FAFu manager is notified of the result.

Extensions:

1. If the Assignment Engine does not obtain a frequency, the FAFu manager can intervene and try to find a frequency.

Special Requirements: None

Issues: None

A.7 Review Assignment Engine Result

Use Case: Review Assignment Engine Result

Description: FAFu manager reviews result and takes appropriate action.

Primary Actor: FAFu manager

Supporting Actors: User

Scope: Assignment Engine and client

Level: User goal

Stakeholders and Interests: UAS operators

Preconditions:

1. FAFu manager logged in to the system.
2. Assignment Engine has run.
3. Message notifying FAFu manager of the result has been sent and received.

Trigger: Message notifying FAFu manager of the result has been received.

Minimal Guarantee: Conflicting CNPC frequencies are not assigned.

Success Guarantee: A non-conflicting CNPC frequency is approved and the user is notified.

Main Success Scenario:

1. Assignment Engine runs and determines available frequency.
2. FAFu manager is notified of the result.
3. The FAFu manager reviews the result and notifies the user of the frequency.

Extensions:

1. If the Assignment Engine does not obtain a frequency, the FAFu manager can intervene and try to find a frequency. The FAFu manager may:
    a. Terminate assignments previously made to UAS operators that have kept frequency assignments past their estimated end times.
    b. Relocate the GS of the requesting UAS operator.
    c. Lower the ceiling or horizontal extent of the requesting UAS operator's SV.
    d. Reduce the transmitter power of the requesting UAS operator's GS or UA.
    e. Change one or more preexisting UAS assignments in a manner that would create spectral "room" for the new UAS operator's CNPC link.
2. The FAFu manager proposes a modification to the user's original request.
3. The user accepts the modification.
4. The FAFu manager notifies the user of the frequency.

Special Requirements: None

Issues: None

Appendix B Sequence Diagram for an Assignment Request

A sequence diagram shows the interaction between objects within a system. Sequence diagrams are constructed based upon use cases to further refine system functionality and requirements. A sequence diagram of the primary FAFu use case (“Request Frequency Assignment”) is shown in Figure B-1.

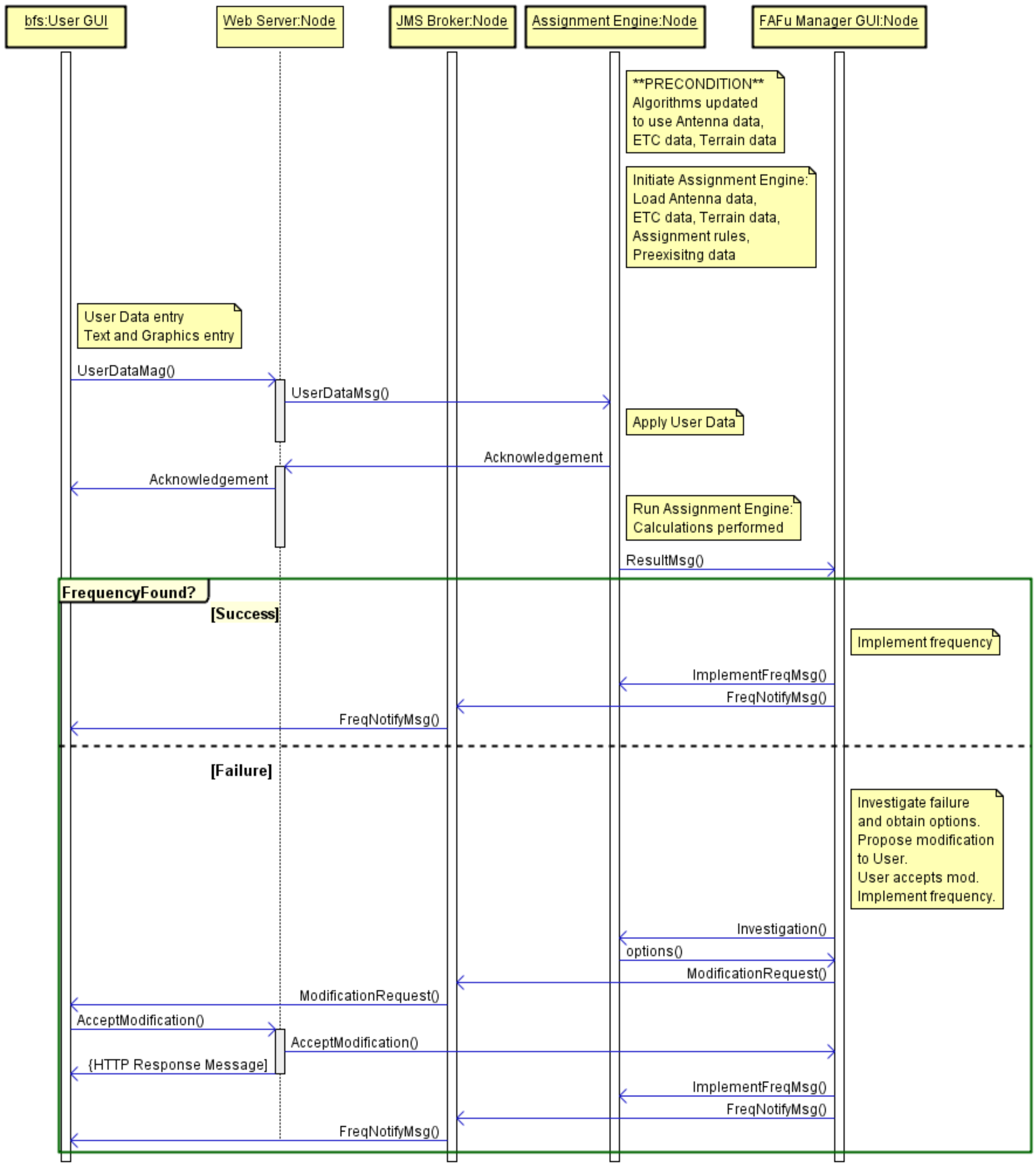

Figure B-1. Request Frequency Assignment Sequence Diagram

The sequence diagram shows several major objects of the FAFu system. The FAFu client is shown in the upper left as User GUI (graphical user interface). The system can be implemented as a Web service with the additional capability of publishing asynchronous messages. The Web Server in the figure represents the Web service and the Java Message Service (JMS) Broker object represents the message publisher. The Assignment Engine object implements the logic required to assign CNPC frequencies. The system also contains a FAFu Manager GUI, which allows the FAFu manager to interact with the system.

The sequence of steps begins after the Assignment Engine has been updated and started. A UAS operator enters desired text and graphical data using the User GUI to describe the desired UAS operations. This causes a UserDataMsg message to be sent from the User GUI to the Assignment Engine via the Web Server. An Acknowledgement message is returned to the User GUI acknowledging that the user data was received. The Assignment Engine then calculates a non-conflicting frequency that can be used by the UAS operator and sends the result in a ResultMsg message to the FAFu Manager GUI. If the FAFu manager determines the frequency is acceptable, the FAFu manager uses the GUI to send an ImplementFreqMsg message to the Assignment Engine to indicate that the assigned frequency has been approved. The FAFu manager also sends a FreqNotifyMsg message to the operator via the JMS Broker to inform the user of the CNPC frequency assignment.

If the Assignment Engine cannot assign a frequency or the FAFu manager does not approve of the calculated frequency, the manager can interact with the Assignment Engine to determine an alternate frequency assignment. The sequence diagram shows an Investigation message sent and an options message received; these messages are illustrative only, since there will likely be many interactions between the FAFu manager and Assignment Engine before an alternate frequency can be identified. Once a frequency is determined, the FAFu manager initiates a ModificationRequest message to be sent to the user via the JMS Broker to request that the user modify their operating parameters to accommodate the frequency selection. The operator accepts the modification by initiating the AcceptModification message, which is sent to the FAFu Manager GUI via the Web Server. The FAFu manager then initiates the ImplementFreqMsg and FreqNotifyMsg messages as discussed previously.

Appendix C Glossary

Acronym	Definition
ACR	adjacent-channel rejection
A/G	air/ground
AGL	above ground level
AMSL	above mean sea level
AR	airborne radio
BLOS	beyond line of sight
C2	command and control
CCPR	cochannel protection ratio
CCW	counterclockwise
CNPC	control and non-payload communications
CONOPS	concept of operations
CSA	Central Spectrum Authority
CSV	circular SV
CW	clockwise
dB	decibel(s)
dBi	dB referred to gain of lossless isotropic antenna
dBm	dB referred to one milliwatt
DF	dual-frequency
DME	Distance Measuring Equipment
E	Eastern (Hemisphere)
EDI	excess-delay interference
EIRP	effective isotropically radiated power
ETC	Equipment Type Characteristics
FAA	Federal Aviation Administration
FAFu	Frequency Assignment Function
FCC	Federal Communications Commission
FDR	frequency-dependent rejection
FL	Florida
GHz	gigahertz
GR	ground radio

Acronym	Definition
GS	ground station
GUI	graphical user interface
ICAO	International Civil Aviation Organization
ID	identifier
IDWM	ITU Digital World Map
IM	intermodulation
IMP	IM product
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
JMS	Java Message Service
kHz	kilohertz
m	meter(s)
MAFS	minimum allowable frequency separation
MHz	megahertz
MLS	Microwave Landing System
MOPS	Minimum Operational Performance Standards
ms	millisecond(s)
N	Northern (Hemisphere)
NACR	non-adjacent-channel rejection
NAS	National Airspace System
navaid	navigational aid
nmi	nautical mile(s)
NTIA	National Telecommunications and Information Administration
NUA	not-very-high-altitude UA
NUAS	not-very-high-altitude UAS
RF	radio frequency
RFI	RF interference
RLOS	radio line of sight
S	Southern (Hemisphere)
SF	single-frequency
SHF	superhigh frequency
SV	service volume

Acronym	Definition
SWIM	System Wide Information Management
TDD	time-division duplexing
TDMA	time-division multiple access
TIREM	Terrain-Integrated Rough-Earth Model
UA	unmanned aircraft
UAS	unmanned aircraft system(s)
UHF	ultrahigh frequency
U.S.	United States
UTC	Coordinated Universal Time
VHF	very high frequency
VUA	very-high-altitude UA
VUAS	very-high-altitude UAS
W	Western (Hemisphere)